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Finite Element Modeling of Cooling Coil Effects in Mass Concrete Systems

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Finite Element Modeling of Cooling Coil Effects in Mass Concrete Systems

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Preface

This report was written to provide the practicing engineer with a detailed methodology for modeling cooling coils in a nonlinear, incremental, structural analysis. The work was sponsored under funds provided to the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS, by Headquarters, U.S. Army Corps of Engineers Civil Works Directorate, under Concrete and Structural Engineering Work Unit 31589 of the Computer Aided Structural Engineering (CASE) Project.

Roberta M. Strigel performed the work, through contract DACW39-99-P-0287. Dr. Kevin Z. Truman provided supervision of all work at Washington University. Mr. Chris A. Merrill, Computer-Aided Engineering Division (CAED), Information Technology Laboratory (ITL), ERDC, was the contracting officer's representative and Dr. Barry Fehl, formerly CAED, managed, coordinated, and monitored the work. Mr. H. Wayne Jones, Chief, CAED, ITL, is the Project Manager for the CASE Project. Mr. Timothy Ables was Acting Director, ITL.

This report is a thesis presented to the Server Institute of Washington University in partial fulfillment of the requirements for the degree of Master of Science.

At the time of publication of this report, Dr. James R. Houston was the ERDC Director, and COL John W. Morris III, EN, was the ERDC Commander and Executive Director.

Chapter 1

Introduction and Literature Review

This first portion of this chapter describes the need for this project and goals upon its completion. The second portion focuses on a summary of previous work in the field.

1.1 Objectives

The general theory for the removal of heat from concrete by embedded cooling pipes was first developed for use in the design of the Boulder Canyon (Hoover) Dam by the United States Bureau of Reclamation in 1949. This was the first application of the mathematical model of heat conduction into a format that could be utilized in the design and implementation of cooling coils to cool a massive concrete system. Subsequent work has been highly dependent on the theory developed for the Hoover Dam.

1.1.1 Non-Linear Incremental Structural Analysis

Over the past decade, the United States Army Corp of Engineers (USACE) has developed and implemented the use of nonlinear, incremental structural analysis (NISA) procedures to predict the effect of thermal loads due to the heat of hydration of cement in massive concrete structures during construction. NISA's have been quite successful in reducing costs of construction and/or providing better performance through the construction specifications. When a dam is constructed, it is built in sections called lifts that are poured one at a time in a particular sequence determined by the specifications of the project. NISAs have been used to recommend insulation requirements, develop appropriate lift dimensions, specify lift placement sequences, and specify concrete constituents in order to reduce construction costs, reduce the potential for cracking and to enhance performance of the structure.

To date, the commercial program ABAQUS has been used to perform a majority of the NISAs due to its versatility. The ABAQUS program can be used to model convection, conduction, heat generation, cracking criteria, lift placement, age dependent material properties within finite element time history analyses. Recently, a need to develop a modeling procedure for NISAs that can account for cooling coils placed within massive concrete structures has arisen. Often the heat generation within the massive concrete structures cannot be controlled by changing the concrete constituents, reducing lift heights/widths, or modifying the construction procedures. Cooling coils placed within the concrete are needed to act as a radiator, constantly carrying heat from the source, the central region of the concrete, in order to reduce the thermal gradient within the material.

A realistic method of modeling the effects of cooling coils in massive concrete structures is presented in this thesis for both 2D and 3D analyses. Being able to capture the thermal changes in the concrete and cooling coils as they occur in time is the primary objective of the modeling technique. Previous to the modeling technique presented here, there was no acceptable procedure for modeling cooling coils and their effects within massive concrete structures using ABAQUS.

1.1.2 Portuguese Dam Project

The specific motive for the development of this modeling procedure is for the Portuguese Dam. The Portuguese Dam is being designed by the Army Corp of Engineers at the time of this study. The modeling procedure developed will be used to assist in the design of the cooling coil system. Parameters from the Portuguese Dam project, such as ambient temperatures, concrete properties, and water properties are used throughout thesis for the development of the model. However, the model can be used for any massive concrete systems, including those that have different parameters and specifications than the Portuguese Dam.

1.2 Organization

Chapter one will very briefly highlight some prior work involving finite element analysis of cooling coils embedded in mass concrete systems. Chapter two will describe in detail the Boulder Canyon Dam theory for the removal of heat by embedded pipes. Chapter two will also discuss ABAQUS capabilities and functions and the preliminary meshes in both 2D and 3D that were used. Chapter 3 will discuss the requirements of the model and modeling procedures that were attempted. It analyzes why particular methods were discarded. Chapter 4 describes in detail the modeling procedures used to model the embedded cooling coils, which is the use of boundary temperatures nodes in ABAQUS. Chapter 4 discusses how the model works, considerations, concerns, and error. Chapter 5 presents results obtained from using the modeling procedure. The results presented are both 2D and 3D, and include 2D analysis of the actual Portuguese Dam model. Chapter 6 describes how to implement the modeling procedure in any mass concrete finite element model. Chapter 7 contains conclusions.

1.3 Literature Review

Three articles involving previous work using finite element analysis to model embedded cooling coils in concrete will be discussed briefly here. In Chapter 2, the Boulder Canyon Dam theory for embedded cooling coils will be discussed at length.

The first solution to the problem of embedded cooling coils used to remove heat from mass concrete systems was solved by the Bureau of Reclamation for the Boulder Canyon Dam project in 1949. The theory that was developed had certain assumptions that will be discussed further in Chapter 2. However, it produced good results and is use for design today. Finite element models were proposed to solve the problem, such as that by E.L. Wilson at the University of California-Berkeley in the 1960's[1]. These models were extended by others to reduce computational time

[1] Wilson, Edward L. and Robert E. Nickell. 'Application of the Finite Element Method to Heat Conduction Analysis.' *Nuclear Engineering and Design.* North-Holland Publishing Company, Amsterdam, August 1966.

using a substructure method of finite element analysis[2] and new theory has been developed[3], including that for nonmetal pipes[4]. However, until this point there was not a finite element modeling procedure available using ABAQUS or a finite element modeling procedure that could easily be used by designers to design the cooling coils systems for massive concrete structures, particularly for NISA analyses.

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[2] Gong, NG and GR Li. *Stress Analysis in Concrete with Cooling Pipes.* Fifth International Conference on Computing in Civil and Building Engineering. Anaheim, California, June 7-9, 1993.
[3] Liu, X.-L., G.-R. Li, J.-S. Jia, and P. Xu. *A Mathematical Model and Finite Element Method in the Solution of Embedded Pipe Cooling of Concrete Blocks.* Advanced Computational Methods in Heat Transfer II, Vol.1: Conduction, Radiation and Phase Change. Computational Mechanics Publications, Boston, 1992.
[4] Zhu, Bofang. 'Effect of Cooling by Water Flowing in NonMetal Pipes Embedded in Mass Concrete.' *Journal of Construction Engineering and Management.* Vol. 125, No. 1, January/February 1999.

Chapter 2

Theory and Methodology

2.1 Boulder Canyon Dam Cement and Concrete Investigations - Cooling of Concrete Dams

Investigations into the artificial removal of heat from the concrete for the Hoover Dam project began out of necessity. When massive concrete structures are constructed, the heat of hydration from the reaction of the Portland cement and water in the concrete is released and thermal stresses are created in the concrete. These thermal stresses can cause extensive cracking and damage to the structural system. Due to the massive size and rapidity of construction of Hoover Dam, a major design issue was the prevention or removal of this excess heat. It was predicated that, without some artificial means of removing the excess heat of hydration, that more than 100 years would be required for the concrete in the dam to attain thermal and volume equilibrium[5].

2.1.1 Artificial Cooling by Water Flowing in Embedded Pipes

The mathematical theory of heat conduction was used to develop the mathematical model for the embedded cooling pipes by the Bureau of Reclamation. The application of the heat conduction theory to the cooling pipes had not previously been documented prior to the construction of Hoover Dam. The Hoover Dam theory has since been used by designers for the development of cooling coil systems[6]. The basics of that theory will be outlined here.

To begin the analysis, consider an infinitely long hollow circular cylinder, whose inner diameter is 'a' and outer diameter is 'b.' The cylinder is insulated at its outer boundary, initially at a uniform temperature, and has zero temperature at its inner surface. The governing heat conduction equation is:

$$\frac{\partial \theta}{\partial t} = h^2\left(\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r}\frac{\partial \theta}{\partial r}\right) \tag{2-1}$$

The variable 'r' represents the radial distance to any point in the cylinder located between the outer diameter 'b' and inner diameter 'a.' The variable θ represents the temperature, h is the diffusivity, and t is time.

The mathematical model must account for certain boundary conditions. These are as follows:

1) $\theta = \theta_o$ when time $t = 0$
2) $\theta = 0$ at $r = a$ and $t = 0$
3) $\frac{\partial \theta}{\partial r} = 0$ at $r = b$ and $t \geq 0$

Assume that the solution is of the form:

$$\theta = \theta_o u e^{-h^2\alpha^2 t} \tag{2-2}$$

where u is a function of r only, α is a constant, and h is the diffusivity of the concrete. Using Bessel's differential equations of order zero, a solution can be obtained in the form of Eq. 2-2:

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[5] United States Department of the Interior, Bureau of Reclamation. *Cooling of Concrete Dams.* Boulder Canyon Project. Final Reports. Part VII – Cement and Concrete Investigations. Bulletin 3, 1949. Denver, CO, page 2.

[6] For a more thorough explanation, the reader should see United States Department of the Interior, Bureau of Reclamation, *Cooling of Concrete Dams.* Boulder Canyon Project, Final Reports. Part VII – Cement and Concrete Investigations. Bulletin 3, 1949. Denver, CO.

$$\theta = \theta_o \sum_{n=1}^{\infty} u_o(\alpha_n r) A_n e^{-h^2 \alpha_n^2 t} \tag{2-3}$$

It is convenient to evaluate Eq. 2-3 by expressing the radius a as some constant times b since a definite value for the ratio a/b will always exist for any given hollow cylinder. If $b=D/2$, then

$$\frac{\theta}{\theta_o} = \sum_{n=1}^{\infty} u_o(\alpha_n b \frac{r}{b}) A_n e^{\frac{4h^2(\alpha_n b)^2 t}{D^2}} \tag{2-4}$$

Therefore, when values are given to the ratios a/b and r/b, the ratio θ/θ_o will be equal for two cylinders of different sizes and thermal properties if the quantity h^2t/D^2 has the same value for both cylinders.

To obtain the mean temperature θ_m of the hollow cylinder, the temperature should be integrated throughout the volume of the cylinder and divided by the volume of the cylinder using Eq. 2-3. The resulting expression will give the mean temperature at a time t for an infinite hollow cylinder, initially at a uniform temperature θ_o throughout, whose outer boundary is insulated and whose inner boundary is kept at zero temperature. After introducing $a_n b$ and $b=D/2$, the following expression analogous to Eq. 2-4 results:

$$\frac{\theta_m}{\theta_o} = \frac{2ab}{b^2 - a^2} \sum_{n=1}^{\infty} \frac{u_o'(\alpha_n b \frac{a}{b}) A_n e^{\frac{4h^2(\alpha_n b)^2 t}{D^2}}}{\alpha_n b} \tag{2-5}$$

By inspection of Eq. 2-5, it is apparent that if a definite value is assigned to the ratio a/b, the ratio θ_m/θ_o will have the same value for two cylinders of different sizes and thermal properties if the quantity h^2t/D^2 is equal for both cylinders. It is assumed for the derivation that the ratio of b/a is equal to 100. Modifications to the design when the b/a ratio is not equal to 100 will be discussed below.

As stated above, the previous discussion was completed for heat flow in an infinite hollow cylinder, initially at a uniform temperature with the outer boundary perfectly insulated and the inner boundary held at zero temperature to simplify the calculations. Therefore, the zero point of the temperature at the inner boundary must be shifted to the cooling coil temperature. The results of the idealized problem of the infinite hollow cylinder described above are used to derive relations for the actual cooling process using cooling water flowing in embedded pipes.

As the water flows through a cooling pipe, heat is transferred from the concrete to the water through convection. Therefore, the longer the water is traveling through the cooling coil in the concrete block, the larger its temperature increase. This results in different rates of cooling at different locations along the length of the pipe as the cooling pipe water temperature increases. The concrete closest to the inlet end will be cooled to a greater extent than the concrete closer to the exit of the pipe. This problem has been addressed by the Bureau of Reclamation by specifying that the cooling coil water flow be reversed every twelve hours during construction of recent dams, leading to an even rate of cooling in the concrete for design purposes. However, the theory created for Boulder Dam accounts for the fact that different cooling rates will exist for all points along the length of the pipe.

Solutions to the actual cooling process using artificial cooling by embedded pipes are given on three sets of graphs referred to as the X, Y, and Z curves. All three graphs depend on two dimensionless parameters, given in equations 2-6 and 2-7.

$$\frac{KL}{c_w \rho_w Q} \tag{2-6}$$

$$\frac{h^2 t}{D^2} \tag{2-7}$$

where:

K = conductivity of concrete

L = length measure along the cooling pipe

c_w = specific heat of water (or other cooling fluid)

ρ_w = density of water (or other cooling fluid)

Q = cooling fluid flow rate

h = diffusivity of concrete

t = time since cooling commenced

D = diameter of the cooled cylinder

The units must be kept consistent in order to create dimensionless parameters. The three graphs are defined as follows:

$$X = \frac{Mean\,temperature\,of\,concrete\,cylinder\,of\,length\,L - inital\,temperature\,of\,water}{Initial\,temperature\,of\,concrete - initial\,temperature\,of\,water}$$

$$Y = \frac{Temperature\,of\,water\,at\,given\,distance\,\text{-}\,inital\,temperature\,of\,water}{Initial\,temperature\,of\,concrete\,\text{-}\,initial\,temperature\,of\,water}$$

$$Z = \frac{Mean\,temperature\,of\,concrete\,at\,a\,given\,length\,L\,\text{-}\,inital\,temperature\,of\,water}{Initial\,temperature\,of\,concrete\,\text{-}\,initial\,temperature\,of\,water}$$

The Y-curves are used to determine the temperature rise of the cooling coil water as it travels through the concrete. The X-curves represent the final mean temperature difference in degrees per degree of initial temperature difference. The Z-curves are used to compute the mean temperature of concrete at a given length from the inlet. As stated earlier, it is current procedure of the Bureau of Reclamation to require that the flow of cooling coil water be reversed every twelve hours. As a result, the mean temperature of the concrete is assumed to be relatively constant throughout the block and the Z-curves are rarely used.

2.1.2 Development of Y-Curves

Across the surface $r=a$, the heat H_o which flows out of the infinite hollow cylinder per unit length of cylinder per unit time is:

$$H_o = \pi\left(b^2 - a^2\right)c\rho\frac{d\theta_m}{dt} \tag{2-8}$$

By differentiating Eq. 2-5 with respect to time (t), we obtain the rate of change of the mean cylinder temperature θ_m with respect to time:

$$\frac{d\theta_m}{dt} = \frac{8ab}{b^2 - a^2} \frac{h^2\theta_o}{D^2} \sum_{n=1}^{\infty} u_o'\left(\alpha_n b \frac{a}{b}\right) A_n(\alpha_n b) e^{-\frac{4h^2(\alpha_n b)^2 t}{D^2}}$$

(2-9)

Substituting $k=h^2 c\rho$ and Eq. 2-9 into 2-8, we obtain:

$$H_o = k\theta_o R \frac{h^2 t}{D^2}$$

(2-10)

where R is defined in Eq. 2-11:

$$R\left(\frac{h^2 t}{D^2}\right) = \frac{4a\pi}{D} \sum_{n=1}^{\infty} u_o'\left(\alpha_n b \frac{a}{b}\right) A_n(\alpha_n b) e^{-\frac{4h^2(\alpha_n b)^2 t}{D^2}}$$

(2-11)

As a result of Eq. 2-11, after defining a/b and the roots $(\alpha_n b)$, values of R may be determined as a function of h^2t/D^2. When $h^2t/D^2=0$, R is equal to R_o.

As stated earlier, the development of this theory accounts for the fact that the water temperature rises as it flows through the concrete cylinder and this accounts for varying rates of heat flow from the concrete to the water in the actual cylinder. In order to do this, a concrete cylinder of finite length is considered. At a distance L from the inlet end of the cylinder and a time λ after cooling has begun, a temperature differential in the cooling water of $\theta_o(\partial Y/\partial\lambda)d\lambda$ will occur. Substituting this temperature differential into Eq. 2-10 for θ_o by making the appropriate change in $R(h^2t/D^2)$ and integrating from 0 to t yields a heat flow per unit length of cylinder per unit time. Summing up these temperature differentials over the length of the cylinder by performing a second integration with respect to L gives the total heat flow per unit of time:

$$H_T = K\theta_o \int_0^L \int_0^t R\left[(t-\lambda)\frac{h^2 t}{D^2}\right] \frac{\partial Y}{\partial \lambda} d\lambda dL$$

(2-12)

Eq. 2-12 is for a hollow concrete cylinder of length L, with initial conditions as stated earlier. This heat will be absorbed by the water in the cooling pipe. The amount of heat absorbed per unit time is:

$$H_T = c_w \rho_w q_w \theta_w \tag{2-13}$$

where the w subscript signifies that the variable is a property of water and θ_w signifies the temperature rise of the water at a given time and distance from the inlet end. If the incoming water temperature is equal to 0, then $Y=\theta_w/\theta_o$. Substituting this expression in Eq. 2-13 gives:

$$H_T = c_w \rho_w q_w \theta_o Y \tag{2-14}$$

Equating equations 2-14 and 2-12 gives:

$$c_w \rho_w q_w \theta_o Y = K\theta_o \int_0^L \int_0^t R\left[(t-\lambda)\frac{h^2 t}{D^2}\right]\frac{\partial Y}{\partial \lambda} d\lambda dL \tag{2-15}$$

Eq. 2-15 is somewhat difficult to solve because it includes Y under an integral on one side and independently on the other side. For this reason, the equation will first be solved for the special case of $h^2t/D^2=0$. In this situation, the temperature of the concrete is θ_o, the temperature of the water at any point along the cylinder is θ_w, and R is equal to R_o as discussed earlier. Under these conditions, Eq. 2-15 becomes:

$$c_w \rho_w q_w \theta_o Y = K\theta_o R_o \int_0^L (1-Y)dL \tag{2-16}$$

The time the cooling water takes to flow through any given coil is assumed to be small compared with the time necessary to cool the surrounding concrete. Let:

$$\xi = \frac{KL}{c_w \rho_w q_w} \qquad d\xi = \frac{K}{c_w \rho_w q_w} dL \tag{2-17}$$

Substitute Eq. 2-17 into Eq. 2-16 and obtain:

$$Y = R_o \int_0^{\frac{KL}{c_w \rho_w q_w}} (1 - Y) d\xi \tag{2-18}$$

If Eq. 2-18 is differentiated with respect to ξ, we obtain:

$$\frac{dY}{d\xi} = R_o(1 - Y)$$

or

$$\frac{dY}{d\xi} + R_o Y = R_o \tag{2-19}$$

This is a first order linear differential equation which has a solution of the form:

$$Ye^{R_o \xi} = e^{R_o \xi} + C_1 \tag{2-20}$$

When ξ and Y are equal to 0, and constant C_1 is equal to -1, then Eq. 2-20 becomes:

$$Y = 1 - e^{-R_o \xi} \tag{2-21}$$

The value of R_o is determined from Eq. 2-11 with h^2t/D^2 equal to 0 and assuming that the ratio of b/a=100. If the first five values of the series in Eq. 2-11 are used, then R_o is equal to 2.693590. Substituting this value in Eq. 2-21 obtains:

$$Y = 1 - e^{-2.693590\xi} \tag{2-22}$$

Eq. 2-22 is used to plot the curve for h^2t/D^2 equal to 0 as shown in Figure 2-1.

Solving Eq. 2-14 for the case of $h^2t/D^2 \neq 0$ is a more complicated process since Y is included within the integral and also independently on the other side of the equation as stated earlier. To begin, let:

$$G = \int_0^t R\left[(t-\lambda)\frac{h^2}{D^2}\right]\frac{\partial Y}{\partial \lambda}d\lambda \tag{2-22}$$

Substituting Eq. 2-22 into Eq. 2-14 obtains:

$$c_w \rho_w q_w \theta_o Y = K\theta_o \int_0^L G dL \tag{2-23}$$

Using the substitutions given in Eq. 1-17, Eq. 1-21 becomes:

$$Y = \int_0^{\frac{KL}{c_w \rho_w q_w}} G d\xi \tag{2-24}$$

Since the above equations include Y independently and under an integral, the solution must follow an iterative procedure that will not be described in detail here[7]. Using this iterative procedure, the Y-curves for values of h^2t/D^2 greater than 0 are obtained. The Y-curves are shown in Figure 2-1.

[7] For a description of this iterative procedure, please see United States Department of the Interior, Bureau of Reclamation. *Cooling of Concrete Dams.* Boulder Canyon Project. Final Reports. Part VII – Cement and Concrete Investigations. Bulletin 3, 1949. Denver, CO. Pages 126-127.

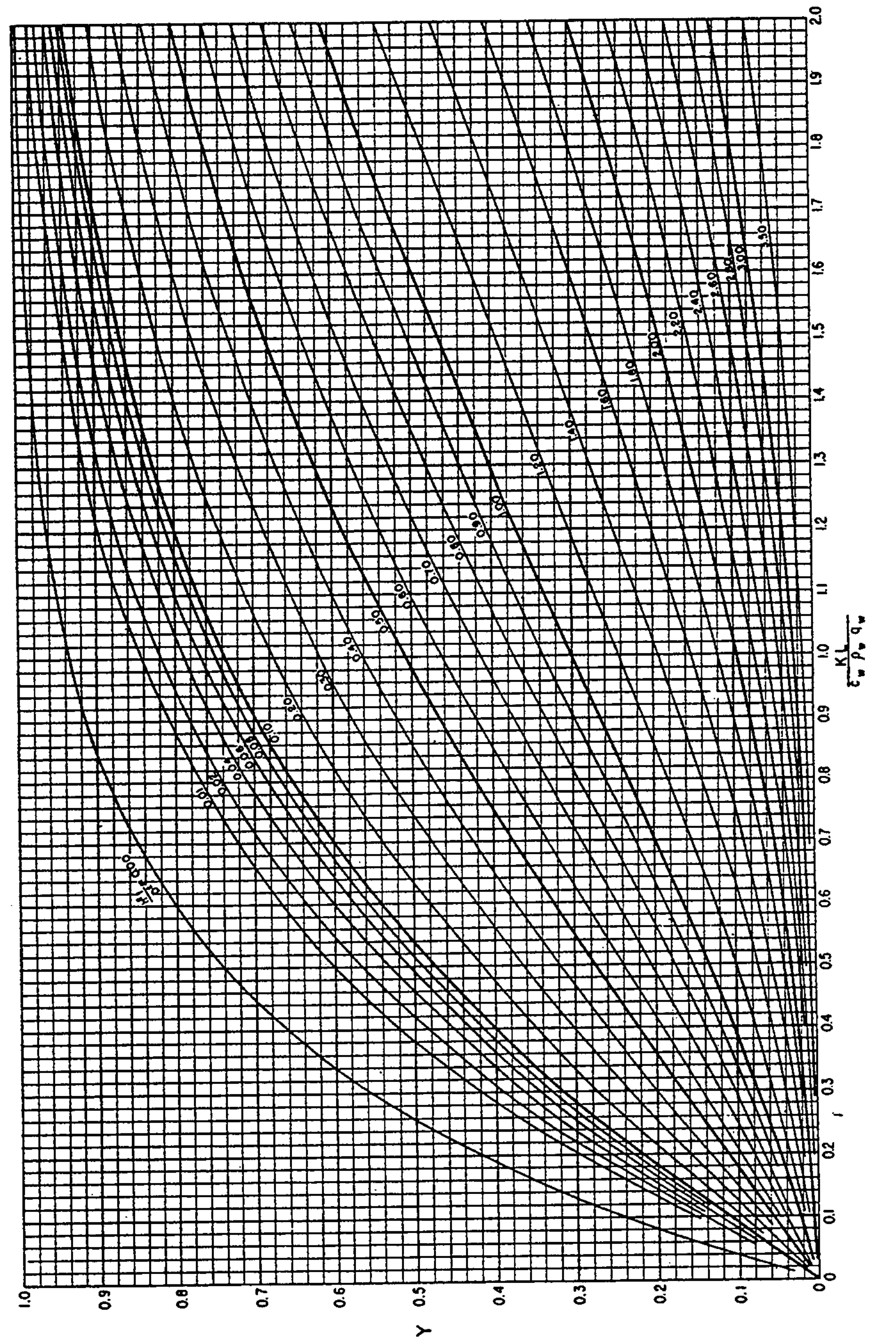

Figure 2-1: *Curves of Y vs. $KL/c_w\rho_w q_w$ for Various Values of h^2t/D^2*[8]

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[8] United States Department of the Interior, Bureau of Reclamation. *Cooling of Concrete Dams.* Boulder Canyon Project. Final Reports. Part VII – Cement and Concrete Investigations. Bulletin 3, 1949. Denver, CO.

2.1.3 Development of Z-Curves

The Z-curves allow us to obtain the mean temperature of the concrete cylinder at any section along the cooling pipe. This mean concrete temperature can be obtained by summing all the increments of mean concrete temperature produced by changes in the temperature of the cooling water up to the time *t*, added to the temperature of the cooling water at time *t*. An increment of mean temperature which occurs at time λ will have been in existence for a period $(t-\lambda)$ at time *t*. The increment of mean temperature produced by an incremental change of $\theta_o(\partial Y/\partial\lambda)d\lambda$ in the temperature of the cooling water may be obtained by Eq. 2-25:

$$(d\theta_m)_i = \frac{2ab\theta_o}{b^2-a^2}\frac{\partial Y}{\partial\lambda}d\lambda\sum_{n=1}^{\infty}\frac{u'_o(\alpha_n b\frac{a}{b})A_n e^{-\frac{4h^2(\alpha_n b)^2(t-\lambda)}{D^2}}}{\alpha_n b}$$

(2-25)

In functional notation, Eq. 2-25 can be expressed:

$$(d\theta_m)_i = \theta_o\cdot\frac{\theta_m}{\theta_o}\left[(t-\lambda)\frac{h^2}{D^2}\right]\frac{\partial Y}{\partial\lambda}d\lambda$$

where:

$$\frac{\theta_m}{\theta_o}\left[(t-\lambda)\frac{h^2}{D^2}\right] = \frac{2ab}{b^2-a^2}\sum_{n=1}^{\infty}\frac{u'_o\left(\alpha_n b\frac{a}{b}\right)A_n e^{-\frac{4h^2(\alpha_n b)^2(t-\lambda)}{D^2}}}{\alpha_n b}$$

(2-26)

The sum of all these increments up to the time *t* will be:

$$(\theta_m)_i = \theta_o\int_0^t\frac{\theta_m}{\theta_o}\left[(t-\lambda)\frac{h^2}{D^2}\right]\frac{\partial Y}{\partial\lambda}d\lambda$$

(2-27)

Then, if Z is the ratio of the mean temperature at the time *t* of any section along the length of the cylinder to the temperature θ_o, then:

$$\theta_o Z = \theta_o Y + (\theta_m)_i \tag{2-28}$$

Combining Eq. 2-25 and Eq. 2-26:

$$Z = Y + \int_0^t \frac{\theta_m}{\theta_o}\left[(t-\lambda)\frac{h^2}{D^2}\right]\frac{\partial Y}{\partial \lambda}d\lambda \tag{2-29}$$

Eq. 2-29 is again solved by graphical iteration that will not be discussed here[9]. This process obtains the Z-curves as shown in Figure 2-2.

2.1.4 Development of X-Curves

The X-curves are used to obtain the mean temperature of the concrete cylinder along its entire length from the inlet end to any particular section along the length. This value can be obtained by taking the Z-curve from zero to the length chosen and dividing by the length. This is described mathematically by:

$$X = \frac{1}{L}\int_0^L Z dL \tag{2-30}$$

Using the variable substitutions from Eq. 2-17, the X-curves are obtained as shown in Figure 2-3.

$$X = \frac{c_w \rho_w q_w}{KL}\int_0^{\frac{KL}{c_w \rho_w q_w}} Z d\xi \tag{2-31}$$

[9] For a description of this iterative procedure, please see United States Department of the Interior, Bureau of Reclamation. *Cooling of Concrete Dams.* Boulder Canyon Project. Final Reports. Part VII – Cement and Concrete Investigations. Bulletin 3, 1949. Denver, CO. Page 129.

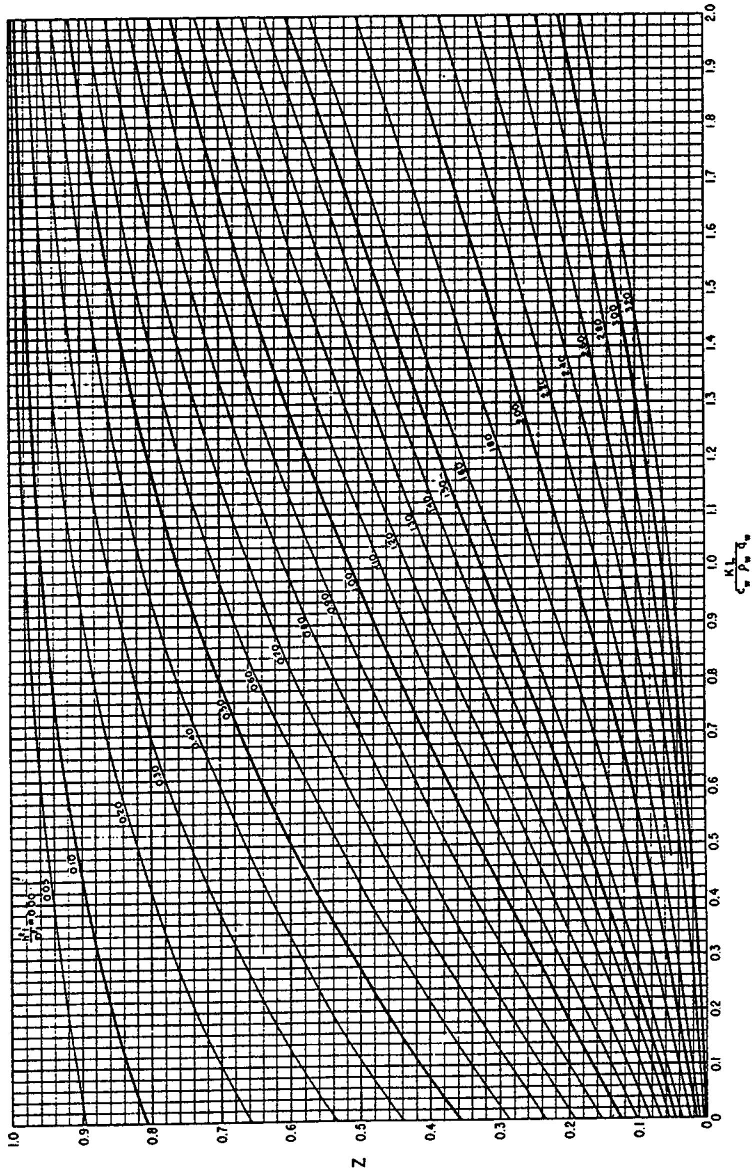


Figure 2-2: *Curves of Z vs. $KL/c_w\rho_w q_w$ for Various Values of h^2t/D^2*[10]

[10] United States Department of the Interior, Bureau of Reclamation. *Cooling of Concrete Dams.* Boulder Canyon Project. Final Reports. Part VII – Cement and Concrete Investigations. Bulletin 3, 1949. Denver, CO.

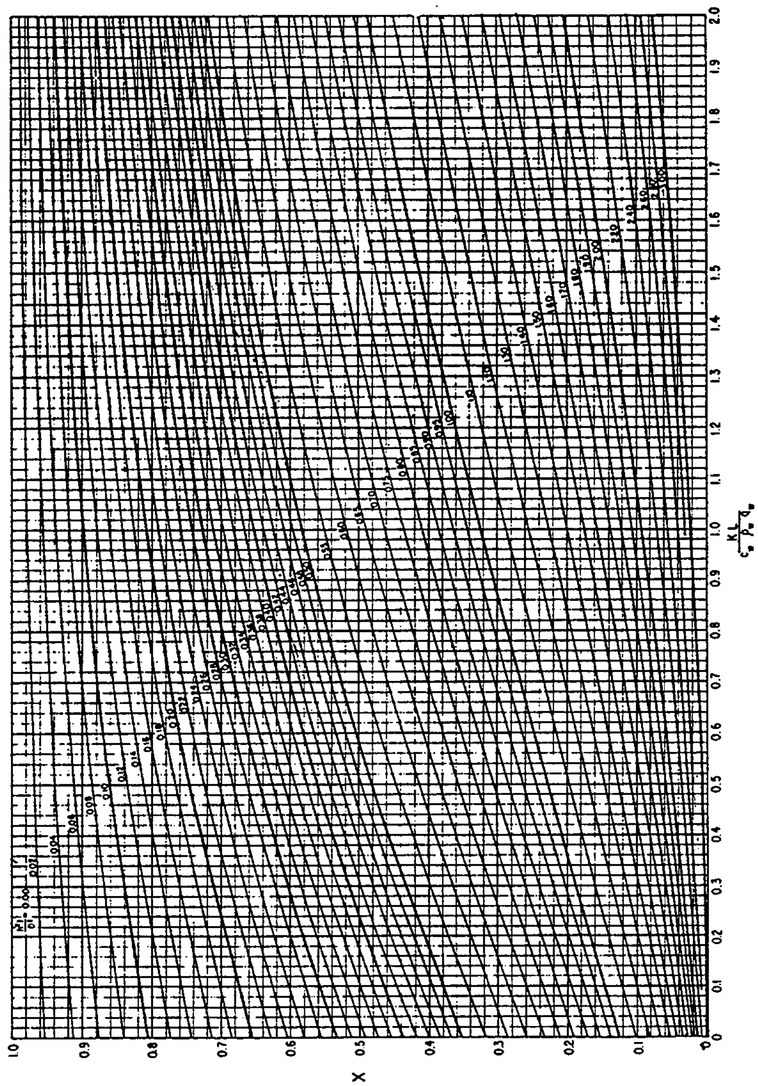


Figure 2-3: *Curves of X vs. $KL/c_w\rho_w q_w$ for Various Values of h^2t/D^2*[11]

[11] United States Department of the Interior, Bureau of Reclamation. *Cooling of Concrete Dams.* Boulder Canyon Project. Final Reports. Part VII – Cement and Concrete Investigations. Bulletin 3, 1949. Denver, CO.

It is important to recognize at this point the development of the X, Y, and Z curves assumed a *b/a* ratio equal to 100, as stated earlier. However, a *b/a* ratio equal to 100 rarely occurs in practice. To account for this discrepancy, but still allow for use of the X, Y, and Z curves, a modification is made to both the diffusivity value (*h*) and the diameter of the cooled cylinder (*D*). These modifications have been calculated by the Bureau of Reclamation for common lift dimensions, as shown in Table 2-1.

Table 2-1: *Values of D, D^2, and h^2_f for Pipe Cooling*[12]

Spacing		D	D^2	h^2_f
Vertical	Horizontal			
feet	feet	feet	$feet^2$	ft^2/hr
2 1/2	2 1/2	2.82	7.95	1.31 x h^2
5	2 1/2	3.99	15.92	1.19
5	3	4.35	18.92	1.16
5	4	5.02	25.2	1.12
5	5	5.64	31.81	1.09
5	6	6.18	38.19	1.07
7 1/2	2 1/2	4.88	23.81	1.13 x h^2
7 1/2	4	6.15	37.82	1.07
7 1/2	5	6.86	47.06	1.04
7 1/2	6	7.54	56.85	1.02
7 1/2	7 1/2	8.46	71.57	1
7 1/2	9	9.26	85.75	0.98
10	2 1/2	5.64	31.83	1.09 x h^2
10	4	7.14	50.93	1.03
10	5	7.98	63.66	1.01
10	6	8.74	76.39	0.99
10	7	9.44	89.13	0.97
10	8	10.09	101.86	0.96
10	9	10.7	114.59	0.95
10	10	11.28	127.32	0.94
10	12	12.36	152.79	0.92
10	14	13.35	178.25	0.91
10	15	13.82	190.99	0.9

[12] From *Control of Cracking in Mass Concrete Structures.* C.L. Townsend, United States Department of the Interior, Bureau of Reclamation. October 1965. Denver, CO.

Another important point worth noting to is that the time value used for the h^2t/D^2 term on the curves is the total time after the start of cooling and includes no heat of hydration of the concrete system. The consequences of this will be discussed extensively in Section 4.1.3.

2.2 ABAQUS

ABAQUS is an engineering modeling program that solves problems using finite element analysis. ABAQUS can solve a wide range of problems, from simple linear analyses to complex non-linear problems, including stress/displacement, heat transfer, mass diffusion, thermal management of electrical components, acoustics, soil mechanics, and piezoelectric analyses. ABAQUS has extensive options available for the element shapes, dimensions, and material types. The modeling procedure discussed in this paper uses ABAQUS/standard, which is a general-purpose analysis module that can solve linear and nonlinear static, dynamic, thermal, and electrical problems.

ABAQUS also offers the incorporation of user written subroutines. Subroutines are offered as options for user control of variables for particular problems. For example, if heat generation is required for the material type modeled in the analysis, ABAQUS can incorporate a user subroutine that contains the FORTRAN code for the calculation of the heat generated during the analysis. ABAQUS then incorporates this subroutine into its analysis. User subroutines can only be used if ABAQUS provides the option of having user control of a variable. They are provided to increase the functionality of the ABAQUS options for which data line usage or predetermined variable values alone may be too restrictive.

2.2.1 Heat Transfer Analysis

ABAQUS can solve uncoupled heat transfer analyses, sequentially coupled thermal-stress analyses, fully coupled thermal-stress analyses, adiabatic analyses, coupled thermal-electrical, and cavity radiation problems. For the modeling of the cooling coils, an uncoupled heat transfer analysis was used. After obtaining the temperature distribution from the uncoupled heat transfer analysis, these temperatures can be used to analyze the thermal stress in the system.

Uncoupled heat transfer analysis is used to model solid body heat conduction with general, temperature dependent conductivity, internal energy, and general convection and radiation conditions. Forced convection of a fluid through a mesh can be modeled using specified elements. This will be discussed further in section 3.5. These problems can be transient or steady-state, linear or nonlinear, and can include thermal interactions such as gap radiation, conductance, and heat generation.

Completing a transient heat transfer analysis with second order elements in ABAQUS can lead to the appearance of spurious oscillations in the solution, particularly in the vicinity of boundaries with rapidly changing temperatures. To avoid this inaccuracy, the characteristic length of the element and the time increment should satisfy the relationship:

$$\Delta t > \frac{\rho c}{6k} l^2 \qquad (2\text{-}32)$$

where Δt is the time increment, ρ is the density, c is the specific heat , k is the thermal conductivity, and Δl is the characteristic length of the element (in this case the distance between two nodes).

2.3 Development of a Preliminary Model

The development of this model was based on the parameters used to construct the Portuguese Dam in Puerto Rico. The Army Corp of Engineers specifications state that the placement temperature of the concrete for this project is 75°F. Heat of hydration of the Portland Cement reaction with water is calculated and input in the ABAQUS model using the subroutine HETVAL. At the end of each increment, the HETVAL subroutine is called. This routine calculates the additional heat added to the concrete due to the heat of hydration based on the length of time the particular lift has been in place. This additional heat is then accounted for by ABAQUS. HETVAL will calculate different values depending on the lift location and time since its placement. After 28 days, the heat of hydration is assumed to be negligible.

ABAQUS allows for the input of boundary conditions to be specified for the analysis. These boundary conditions are prescribed at nodes for specified degrees of freedom, such as displacement or temperature. These boundary conditions can be constant, or they can be defined to vary according to an amplitude curve that defines the magnitude of the prescribed boundary conditions. The lifts will be cooled (or heated) by external temperature conditions as the exterior faces of the lifts are exposed to the ambient temperature of the surrounding air. For this particular project, ambient temperature conditions at the dam site in Puerto Rico were used as boundary temperatures. The ambient temperature was defined by an amplitude function defining the seasonal variation in temperature, with an average temperature of 78°F, with 83°F and 73°F as the two extremes.

Knowledge of the cooling pipe characteristics was necessary to develop the model. The cooling fluid used in the model is water with a flow rate of four gallons per minute. The cooling coils themselves had a one inch outer diameter and a 0.887 inch inner diameter. The density of concrete is 156.3 psi, conductivity is 19.13112 BTU/day/°F/ft., and specific heat is 0.17 BTU/lb/°F. It is important to note that none of these values are set; the model allows for the variability of any of these parameters.

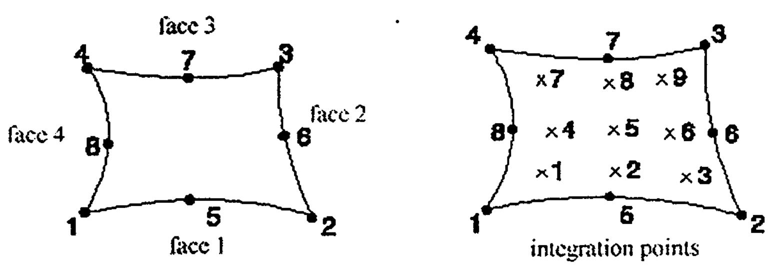
2.3.1 2D Preliminary Mesh

A 2D preliminary mesh was developed to test various methods of modeling the cooling coils. This mesh was small and simple to ensure that an attempted method could be analyzed without complications from the attributes of the mesh. The Army Corp of Engineers uses 2.5-foot element dimensions for the Portuguese Dam, determined by the material properties as shown in Eq. 2-32. The preliminary mesh developed here used two-foot elements for two reasons. The first was to ensure that Eq. 2-32 was satisfied. Secondly, it was anticipated that the cooling coils may need to be placed at node locations. If the total length of the elements was two feet, this allowed for the cooling coils to be placed at various spacings that are multiples of two feet.

When a dam is constructed, it is built in sections called lifts that are poured one at a time in a particular sequence determined by the specifications of the project. The lift dimensions are typically five to ten feet in the vertical direction, with varying horizontal dimensions. For the preliminary mesh, two lifts were modeled. Each lift had a vertical height of ten feet and a horizontal dimension of 16 feet. During construction, vertical lifts will be placed in seven-day increments. As a lift is finished, cooling coils are laid on the top of the finished lift and the new lift will be poured directly on top of the cooling coils. This sequencing means that each lift will be cooled by cooling coils at the boundaries between the lift interface above and below the current lift. Therefore, the two lift preliminary mesh was analyzed for cooling coils placed at the two-lift interface.

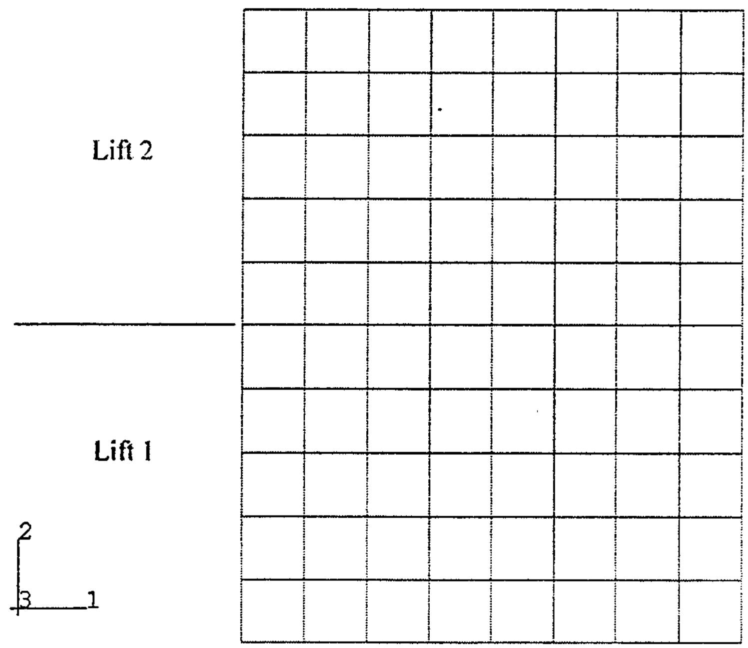
Elements used in the model were second order heat transfer elements type DC2D8. These are eight node quadratic elements with nine integration points as shown in Figure 2-4.

Figure 2-4: *8-Node Quadratic Element*



Second-order elements provide higher accuracy than first-order elements for smooth problems that do not involve complex contact conditions, impact, or severe element distortions and reduce the number of elements required. The DC2D8 elements have an active degree of freedom '11' which is the temperature degree of freedom. Material characteristics were defined for all elements with the concrete parameters discussed above. The 2D preliminary mesh is shown in Figure 2-5. The ambient temperature was applied as the top and bottom boundary condition, and symmetry boundaries were applied to the right and left side.

Figure 2-5: *2D Preliminary Mesh*



2.3.2 3D Preliminary Mesh

As in the 2D mesh, the 3D mesh included two, ten-foot vertical lifts. The lifts had a horizontal width of 16 feet, and a depth of 10 feet. Again the cooling coils were placed at the two-lift interface. Element type DC3D20 was used. These elements are 20-node quadratic brick elements with an active degree of freedom '11' which is the temperature degree of freedom. This element is shown in Figure 2-6.

Figure 2-6: *20-node Element*

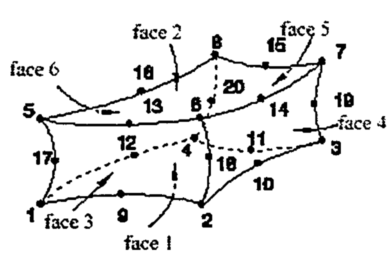
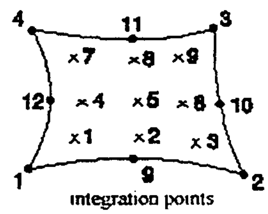


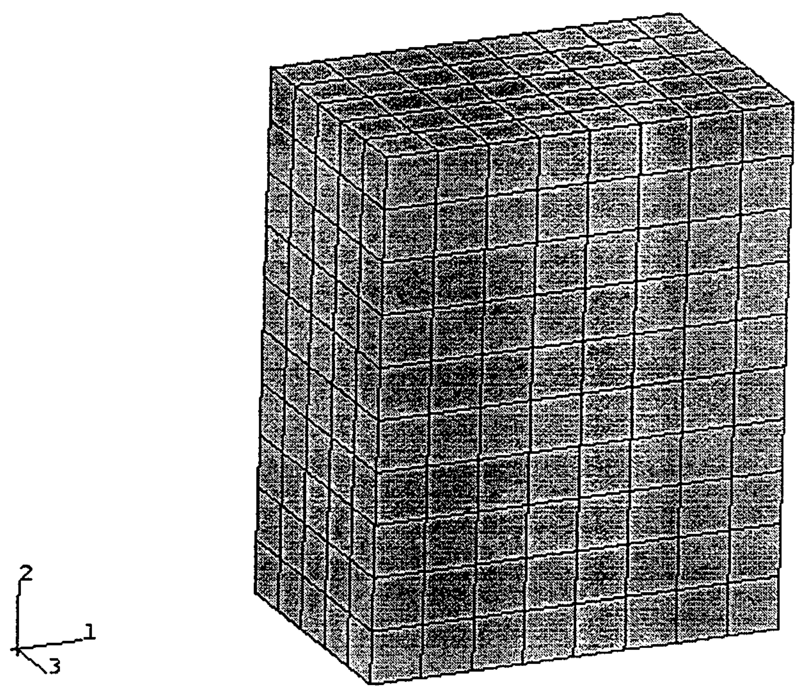
Figure 2-7 shows the integration scheme in the layer closest to the 1-2-3-4 faces. The integration points in the second and third layers are numbered consecutively.

Figure 2-7: *20-node Element Integration Points*



The 3D preliminary mesh is shown in Figure 2-8.

Figure 2-8: *3D Preliminary Mesh*



2.4 Summary

The theory developed to design the cooling system for Boulder Canyon Dam by the Bureau of Reclamation has been used in the past with good results to predict the concrete temperatures in a massive concrete structure cooled by embedded coils. This theory will prove valuable to the development of the model presented in this thesis as well. The preliminary meshes, both in 2D and 3D, presented in this chapter will be used in Chapter 3 to evaluate the validity of potential modeling procedures.

Chapter 3

Modeling Procedures

This chapter will outline the general approach taken to determine the best method for modeling the cooling coils. Approaches were attempted and evaluated for validity using the simple preliminary meshes described in Chapter 2. Using the preliminary mesh, the effect of the methods attempted could be easily evaluated because the mesh itself was uncomplicated.

3.1 Model Requirements

The Army Corp of Engineers wanted to implement a procedure to be used to evaluate cooling coil designs in both two dimensional and three-dimensional models. Anticipating the time of analysis and complexity required for the 3D model, the 2D model will be used to evaluate different cooling coil spacings. When the best spacing is determined, this spacing will be implemented in a 3D model to find the temperature distribution in the concrete. These temperatures will then be used to determine the thermal stresses. The procedures used to evaluate the cooling coils could be different for both the 2D and 3D. However, if they were the same or similar, it would help minimize confusion and mistakes during implementation.

The procedure used to implement the cooling coils in an ABAQUS model had several requirements. The procedure itself was to be used by engineers at the Army Corp of Engineers for the design phase of massive concrete systems to help design the cooling coils. Typically, the design engineers will have already created complicated 2D and 3D models of the proposed dam or other structure. Therefore, the cooling coil procedure needed to be easily input into an existing model without modifying the major characteristics of the existing model such as the element size or node spacing. In addition, the procedure needed to be as uncomplicated as possible to minimize the time required for implementation into an existing model and to limit the frequency of errors made.

It was also necessary to limit modifications to the procedure that are dependent on the specific problem being designed. The more changes the user would need to make to the procedure or code, the more opportunities for errors during use, particularly if these changes required FORTRAN coding by the user.

The amount of heat that the cooling coil removes from the concrete is dependent on the differential temperature between the concrete and the water. The input temperature of the water is constant because the construction specifications require that the water leaving the concrete be cooled to the specified inlet temperature before being recycled through the concrete. As the cooling water moves through the concrete, it becomes warmer as it absorbs heat from the concrete. Therefore, the concrete at the input point of the coil will have a larger rate of cooling than the concrete at the exit point of the water because the temperature differential will be larger at the input. To avoid the occurrence of different rates of cooling in different portions of the lift, it is assumed that construction specifications require that the water flow be reversed every twelve hours. Therefore it will be assumed that the rate of cooling through the concrete block is relatively constant.

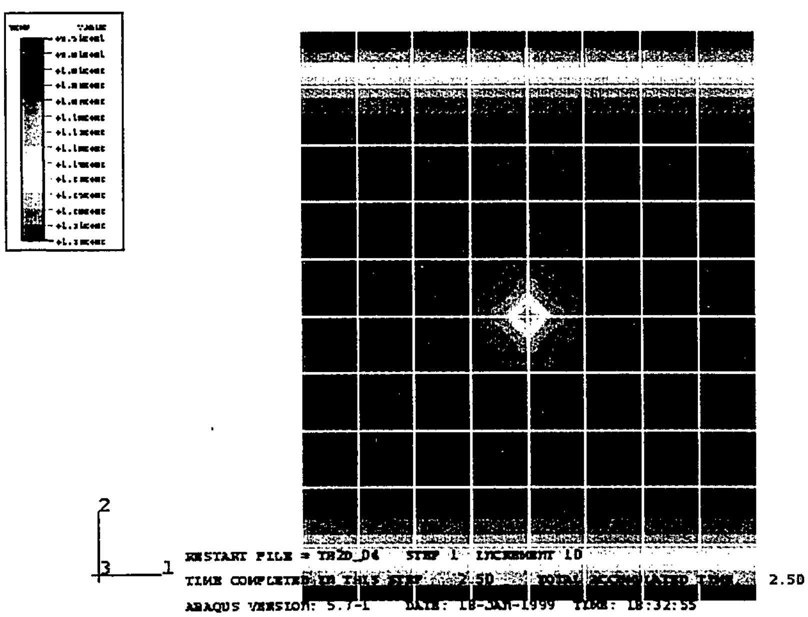
The last concern is that the cooling coils are not operational at all times. They are used initially to control the peak temperature due to heat generation. Then they are shut off, and turned on again to help control the cooling regulating the closure of the grouted joints. Therefore, a method that could be turned off and on at different points in the analysis was necessary.

3.2 CFLUX and DFLUX

The first method attempted was using the two flux options available from ABAQUS. The flux options are a type of thermal loading. CFLUX is used to specify a concentrated heat flux at a node. The DFLUX option is used to specify distributed surface fluxes (on element faces) or body fluxes (flux per unit volume). The flux option can be used to specify the rate at which heat is leaving the mesh. Using DFLUX is not an option because the cooling coils are very small (1" diameter) compared to the element surface (2' x 2'). Therefore, applying a heat flux over the element surface would not be an accurate representation of the manner in which the cooling coil removes heat from the concrete.

Using CFLUX, an arbitrary heat flux was prescribed at a node to determine whether this would remove heat from the concrete mesh as shown in Figure 3-1. All nodes had an initial temperature of 100°F and heat generation was included. The length of the run was 2.5 days.

Figure 3-1: *CFLUX (Scale: maximum 145°F, minimum 92.1°F, interval 4°F)*

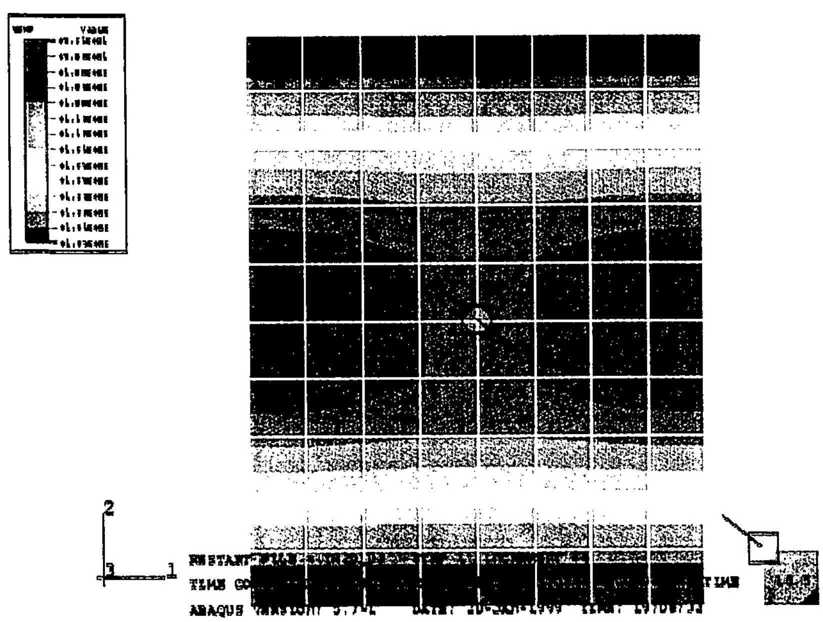


The cooled edges on the top and bottom of the mesh are the boundaries with the ambient temperature applied. This plot demonstrates that applying a flux to the central node in the mesh did remove heat from the system via the central node where the flux was applied. However, CFLUX does not have a user subroutine available to allow the user to write code to modify the flux rate. It only allows for the flux rate to be constant or controlled by a prescribed amplitude function. This is not adequate because the rate of cooling will change with time since due to the effects of heat generation and the difference in the heat absorbed by the water as the temperature of the concrete increases and decreases.

3.3 Gap Elements

Gap elements allow for contact between two nodes which are either adjacent to one another or have a specified separation. One-dimensional gap elements can be used to connect any two elements in a mesh. The gap can then be defined to have a specific heat conductance, electrical conductance, flow for pore pressure elements, heat generation, or radiation. These elements could potentially be used to remove heat at the location of a cooling coil in the mesh, and distribute it to an arbitrary added element that is not part of the actual model. This was completed as shown in Figure 3-2.

Figure 3-2: *Use of a Gap Element (Scale: maximum 134°F, minimum 95.1°F, interval 3°F)*



The model shown had a DINTER type one-dimensional heat transfer element connecting the location of the cooling coil in the center of the mesh to an additional element separate from the mesh. The gap had a defined gap conductance, gap clearance, average temperature, and average mass flow rate per unit area. The elemental interface also was defined to have an element cross-sectional area and an x, y, and z-direction cosine. The extra element was given concrete properties and an initial temperature equal to the input temperature of the cooling coil water.

It can be seen in Figure 3-2 that the use of the gap element does remove heat from the system and transfers it to the additional element connected by the gap. However, it was determined that it was not possible to modify this method to model the actual cooling coil problem. The rate that heat will be transferred out of the concrete is again dependent on the temperature differential between the water and concrete. Using this gap element, the temperatures could not be controlled because there was no subroutine available except GAPCON to modify the gap conductance. Also, as the additional element became warmer, the rate at which heat would leave the concrete would slow. This is true in the real life situation also, but could not be accurately modeled in this case. At some point it could even be assumed that the additional element could heat up to the temperature of the concrete and no longer work as a cooling coil. In addition, the ease of use is not optimal because this option requires the addition of several additional elements to the system, then the connection of all the potential cooling coil nodes to the additional elements. It would need to be determined whether many nodes could be gap connected to the same element or if the rate of heat transfer would be affected by the number of gaps attached. In light of these potential problems and the apparent difficulty of accurately modeling the actual problem using this method, a different method was desired.

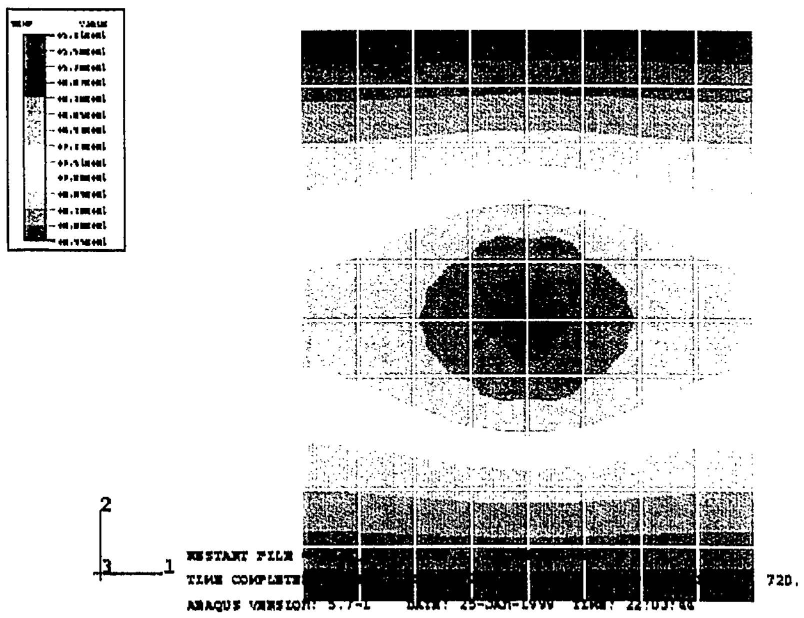
3.4 Boundary Nodes

Boundary conditions can be used to specify the values of all basic solution variables at nodes including displacements, rotations, pore pressures, temperatures, electrical potentials, normalized concentrations, or acoustic pressures. They can be assigned as 'model' input data to define zero-valued boundary conditions or 'history' input data to add, modify, or remove zero-valued or non-zero boundary conditions. Subroutine 'DISP' is available to define or redefine any magnitudes of prescribed boundary conditions.

Boundary conditions can be used in heat transfer analyses to specify boundary temperatures during the analysis. If these boundary temperatures are included at nodes within the mesh, they will act as heat sources or sinks depending on the specific conditions of the problem. The BOUNDARY option was included in the preliminary mesh to test the affects of the boundary temperature as a heat sink. The result is shown in Figure 3-3.

Figure 3-3: *Preliminary Mesh with BOUNDARY Condition*

(Scale: maximum 89.5°F, minimum 52.1°F, interval 2.88°F)



This plot demonstrates the effect of a heat sink after 720 days. Again, the ambient temperature is applied to the top and bottom boundaries and a symmetry boundary to the two sides. It is clear from this plot that the node in the center of the mesh with the temperature boundary condition is acting to cool the system. This method was eventually chosen to model the coils and will be discussed at length in Chapters 4, 5, and 6.

3.5 Forced Convection Through a Mesh

Forced convection of a fluid through the mesh can be modeled in ABAQUS. Forced convection/diffusion heat transfer elements are used and the velocity of the fluid moving through the mesh is prescribed using the MASS FLOW RATE option. This type of analysis is intended for use in thermal problems involving heat transfer in a flowing fluid so that heat is transported (convected) by the velocity of the fluid and additionally is diffused by conduction through the fluid and its surroundings. The mass flow rate of the fluid through the mesh affects the conduction between the fluid and the adjacent forced convection/diffusion heat transfer elements.

3.5.1 Peclet and Courant Numbers

The numerical solution of the transient heat transfer equation including convection becomes more complicated as convection dominates diffusion. The Peclet number (γ), shown in Eq. 3-1, gives a representation of convection dominance over diffusion. The Peclet number should be kept below 1000.

$$\gamma = |\vec{v}| \Delta l \frac{\rho c}{k} \tag{3-1}$$

Where $|\vec{v}|$ is the magnitude of the velocity vector and Δl is the characteristic length of the element in the direction of flow. If $\gamma=0$, this implies no convection because there is no fluid velocity. As $\gamma \rightarrow \infty$, the problem becomes purely convective because there is no time for diffusion. Petrov-Galerkin finite element are used in ABAQUS to model systems with high Peclet numbers. These elements control numerical diffusion and dispersion by using non-symmetric, upwinded weighting functions and stabilize results.

Convection/diffusion elements with numerical dispersion control have a numerical stability limit on the allowable time increment. This requirement is defined by the Courant number. The Courant number is:

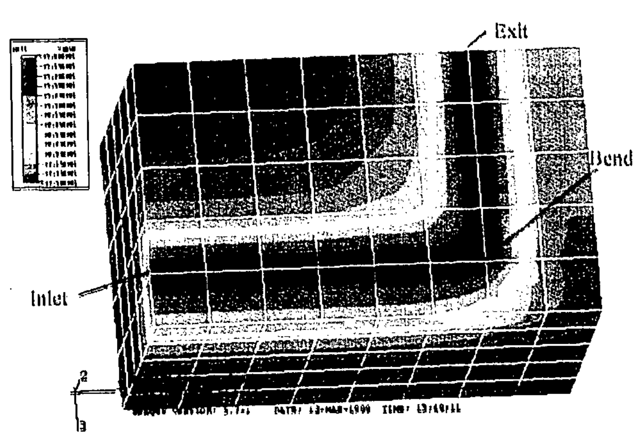
$$C = v \frac{\Delta t}{\Delta l} \tag{3-2}$$

Where v is the velocity of the fluid, Δt is the time increment specified in the analysis, and Δl is the characteristic element length. The Courant number measures how quickly energy can be convected across and element compared to the time increment. If convective/diffusive elements are used in ABAQUS, they cannot provide accurate transient solutions for $C > 1$. If $C > 1$, energy can convect across more than a single element in a time increment.

The Portuguese Dam problem has a flow rate through the cooling coil of 4 gal/min and a 0.887" inner pipe diameter as mentioned earlier. This corresponds to a Peclet number of 1392 using two foot, eight-noded elements that have a characteristic length of one foot (node-to-node distance). However, long before the Peclet number reaches the 1000 limit recommended by ABAQUS, the Courant number exceeds one and the analysis has become unstable. Since the Courant number limit is exceed at a much lower threshold than the Peclet number for the mesh used for the dam problems, it is the limiting criteria for stability and is discussed in greater length below.

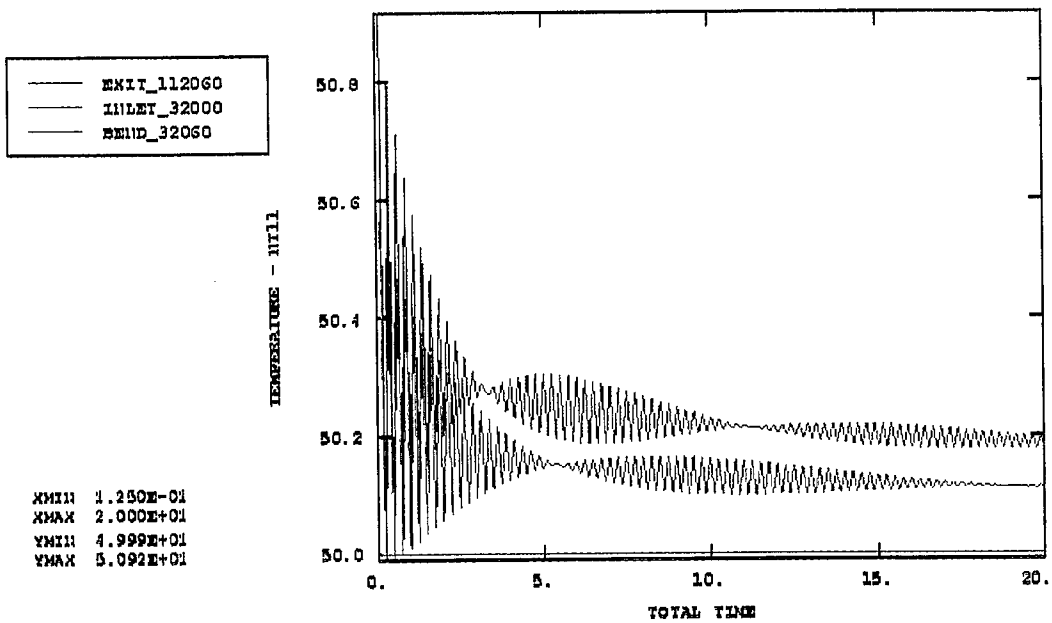
The Courant number for the Portuguese Dam problem is 45,000 for the smallest time increment used (1/4 days). It increases for all the larger time increments used during the analysis. As stated above, the Courant number should be less than one. Having a Courant number of 45,000 is a huge variation from one, and completely destroys the stability of the analysis. Typically, the water flowing through the mesh should pick up heat from the mesh. Therefore, the temperature of the concrete surrounding the coil should gradually decrease, and the water in the coil should increase in temperature. When the solution breaks down, oscillations are seen in the temperature solutions, and the temperatures are not accurate. A 3D analysis was completed on the mesh shown in Figure 3-4. One dimensional convection diffusion elements were placed in an 'L' shape in the model to represent the flowing fluid through the mesh. The flowing fluid is cooling the mesh, as shown by the temperature contours present in the mesh in Figure 3-4.

Figure 3-4: *3D Mesh with Convection/Diffusion Elements to Model Flowing Water (Scale: maximum 75°F, minimum 50°F, interval 1.92°F)*



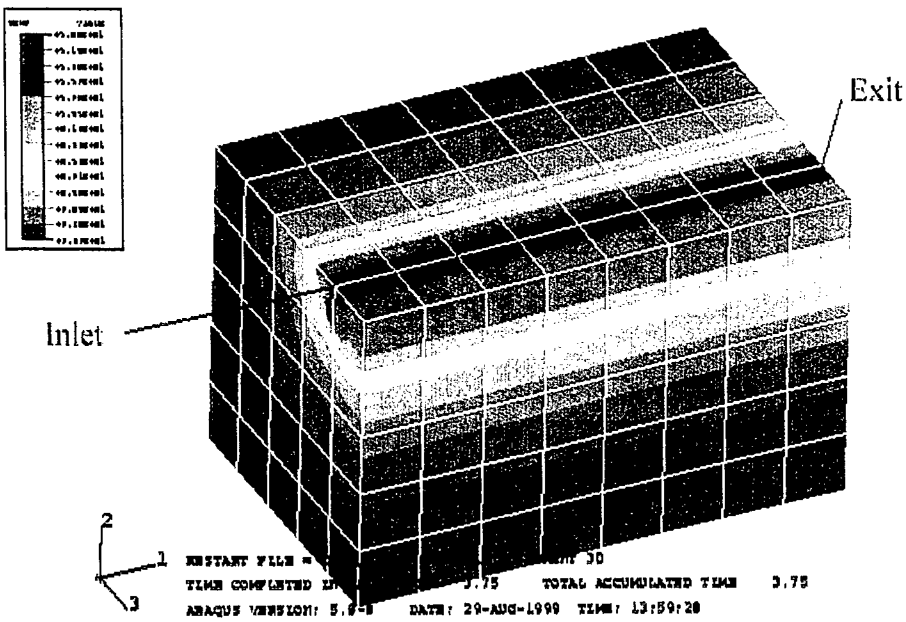
However, a closer analysis of the cooling coil water temperatures in Figure 3-5 shows the breakdown in the solution to oscillating, inaccurate temperatures of the cooling water in the solution. The straight line at 50°F on the graph is the input temperature of the water. The two oscillating curves represent temperatures of the flowing fluid at the bend and exit point respectively along the flow length.

Figure 3-5: *Oscillations in Destabilized Solution due to High Courant Number*



To analyze the affects of elevated Courant numbers on the accuracy of the analysis, the point of breakdown in the analysis was located. To do this, parameters of the Portuguese Dam problem were kept constant except for the flow rate of the water using the preliminary 3D mesh and a straight 16' cooling coil as shown in Figure 3-6. Figure 3-6 shows one-half the model; the top lift is removed in order to view the cooling coil placed between the two lifts. The initial temperature of the concrete is 75°F, the inlet temperature of the water is 50°F, and no heat generation is included in the concrete.

Figure 3-6: *Mesh to Analyze Courant Number Variation With 16' Cooling Coil (Scale: maximum 74.7°F, minimum 50°F, interval 2.9F)*



The mass flow rate corresponding to 4 gallons/minute and a 0.887" diameter pipe is 248,000 slugs/day/ft^2. This corresponds to the Courant number of 45,000 for a ¼ day increment mentioned earlier for the Portuguese Dam problem. When the Courant number reaches one, the solution does not immediately break down and begin oscillating. The solution begins to show signs of stability problems with Courant numbers higher than 1.6, and get progressively worse as shown in the figure series to follow. Figure 3-7 and 3-8 show stable solutions with Courant numbers of 0.9 and 1.6, and mass flow rates of 13.968 slugs/day/ft^2 and 24.832 slugs/day/ft^2 respectively for a five day time period. The temperature plotted is the temperature of the cooling water at the cooling pipe exit point as shown in Figure 3-6. The inlet water temperature is 50°F.

Figure 3-7: *Courant Number of 0.9; Mass Flow Rate of 13.968 slugs/day/ft²*

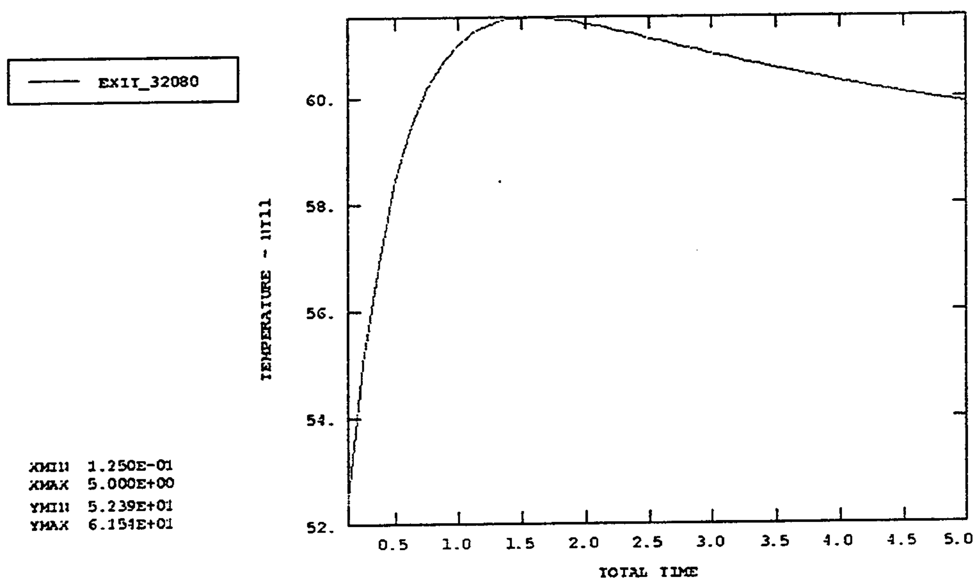
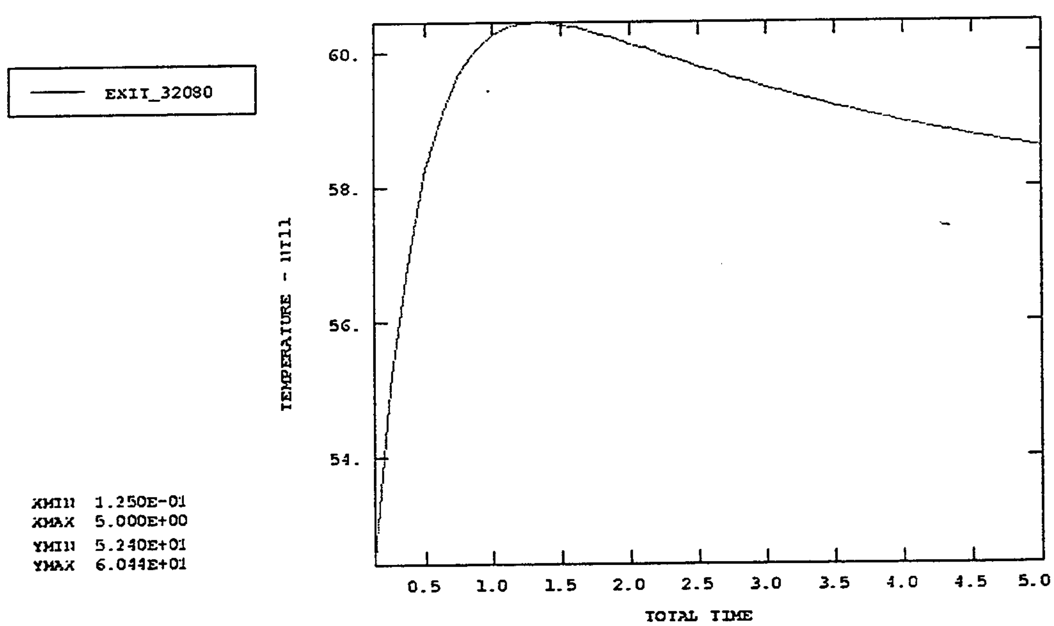
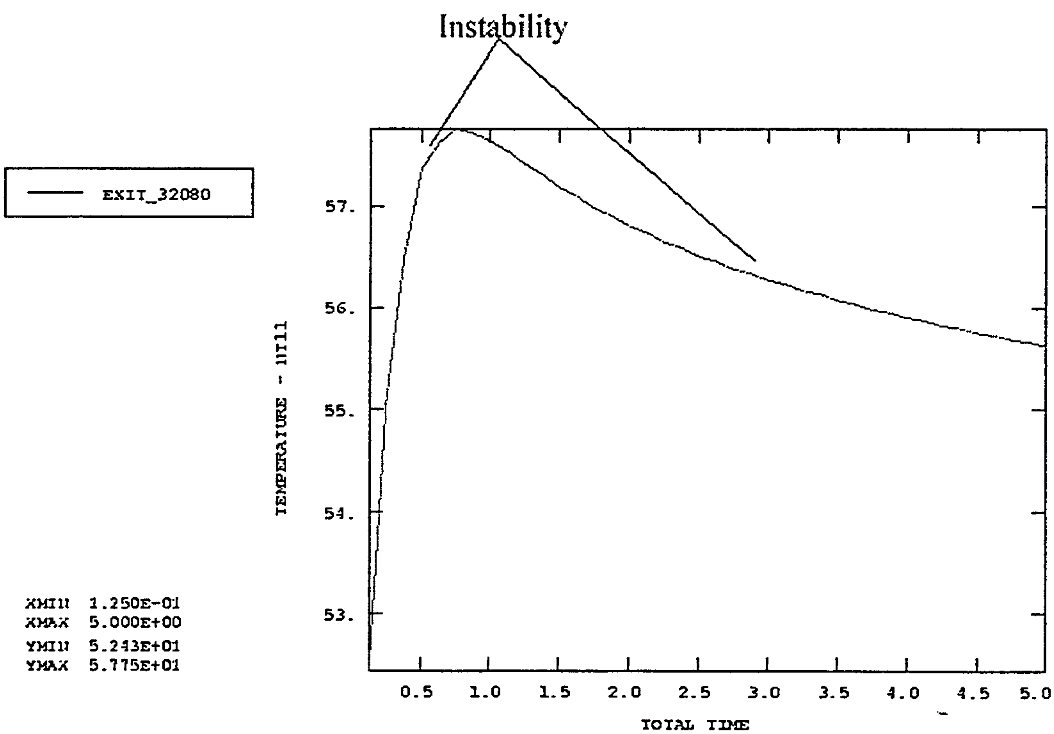


Figure 3-8: *Courant Number of 1.6; Mass Flow Rate of 24.832 slugs/day/ft²*



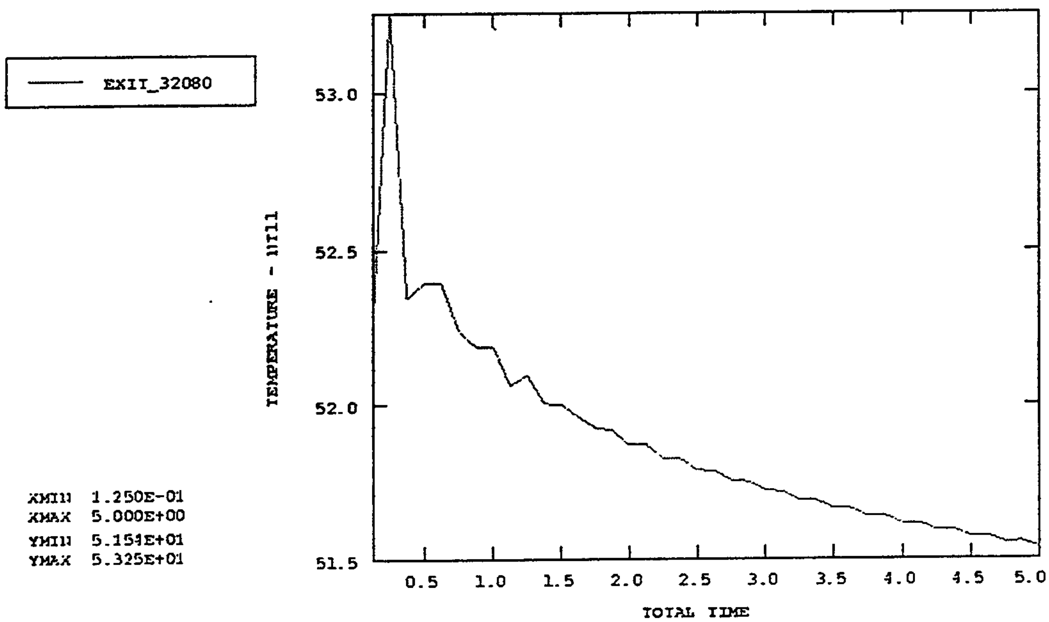
The two solutions shown above are stable, even though the Courant number is 1.6 in Figure 3-8. This can be interpreted to mean that a cutoff Courant number is a safe guideline to follow, however stability in the solution may occur for Courant numbers slightly higher than 1. As the Courant number continues to increase with higher mass flow rates, instability is first seen in the descending portion of the temperature curve as shown in Figure 3-9 for a Courant number of 4.0 and mass flow rate of 62.08 slugs/day/ft^2.

Figure 3-9: *Courant Number of 4.0; Mass Flow Rate of 62.06 slugs/day/ft^2*



The instability is viewed as a loss of the smoothness on the first portion of the curve prior to the peak and in the descending portion of the curve as slight oscillations begin to form. More serious degradation of the solution is viewed by Courant number 19.33 corresponding to a mass flow rate of 300 slugs/day/ft^2 as shown in Figure 3-10.

Figure 3-10: *Courant Number of 19.33; Mass Flow Rate of 300 slugs/day/ft²*

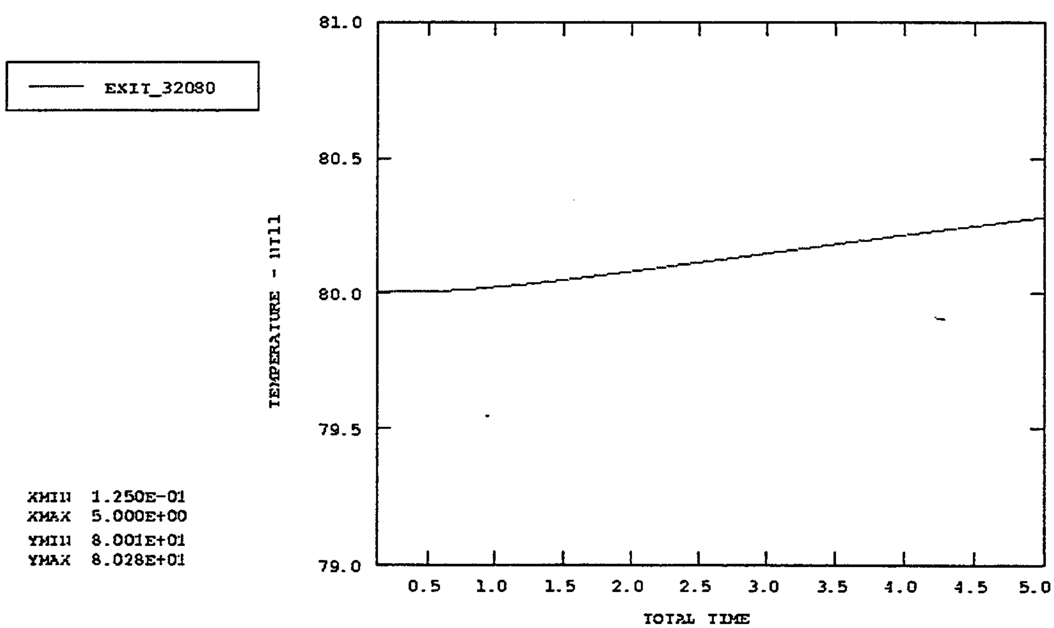


Almost total collapse of the solution is viewed as location of the peak temperature is severely compromised and oscillations are becoming more apparent. As the Courant number continues to increase, complete collapse of the solution with full oscillation of the temperature occurs as demonstrated previously in Figure 3-5.

3.5.2 Limitations of Forced Convection Through Mesh

Several things are of note at this point. The first is that for the analysis shown in Figure 3-10, the Peclet number is only 1.2. This is well below the 1000 limit recommended by ABAQUS for solution accuracy. This demonstrates that in these cases, stability due to the Courant number is by far the limiting case in the analysis. It is also important to recognize that by a Courant number of 19.33 as shown in Figure 3-7, the solution has degraded to the point that all accuracy is lost. This corresponds to a mass flow rate of 300 slugs/day/ft^2. As stated earlier, the flow rate of the Portuguese Dam problem corresponds to a mass flow rate of 248,000 slugs/day/ft^2. Based on this comparison, it is not possible that the Portuguese Dam problem can be accurately modeled using this method. One alternative considered was to attempt to use similitude within ABAQUS to solve the Portuguese Dam problem by decreasing the flow rate and modifying other parameters, such as the conductivity, density, or specific heat of the concrete or water, in order to obtain the correct solution. Several problems were encountered with this method. The first was that when the parameters of the water and concrete were modified, the shape of the temperature curve varied from the shape demonstrated in the above figures. This leads to the conclusion that the solution can no longer be trusted for accuracy. This type of problem is demonstrated in Figure 3-11. The problem modeled was the same as the problems modeled above, however the specific heat and density of water were changed to accommodate the decreased flow rate corresponding to a Courant number of 0.4 for stability. It was a possibility that the solution to this problem would also be the solution to the actual problem.

Figure 3-11: *Courant Number of 0.4; Density and Specific Heat of Water Modified*



It is clear from this plot heat is not being absorbed by the cooling water in the same manner as the earlier plots leading to questions regarding the solution's validity. A second problem encountered was that even if the solution could somehow be obtained through modification of different parameters, it would only hold for a particular increment size. This was not considered adequate because the time increment needs to be changed throughout the analysis or the computational effort would be too great.

3.6 Summary

Upon analying several possible methods for modeling the embedded cooling coils, it was determined that the use of boudnary temperature nodes would be most effective. This will be described in great detail in the following chapters. The forced convection through a mesh capabilities of ABAQUS also demonstrated promise. Although this method cannot be accurately utilized for models of the magnitude and flow rates presented here, there is the possibility for future work in this area to verify the Y-curves.

Chapter 4

Boundary Temperature Model

The use of a boundary condition to control the temperature at locations of cooling coils to act like a heat sink is discussed briefly in section 3.4. However, to accurately use boundary temperatures as cooling coils heat sinks, it is imperative that the cooling coil boundary temperature be accurate. As already discussed, as the water flows through the mesh it absorbs heat from the mesh. The amount of heat removed from the mesh by the water, and the corresponding increase in the water temperature, is partially dependent on the differential temperature between the concrete and the water. It is simply not enough to keep the boundary temperatures at the inlet temperature because this would be assuming greater cooling than what actually occurs because the cooling water temperature will increase as the concrete temperature increases. To determine the water temperature, the theory developed during the Boulder Canyon Dam studies presented in Chapter 1 is used.

4.1 Description of Boundary Temperature Model Process

The Y-curves created during the Boulder Canyon Dam analysis were used to determine the water temperature. As discussed above, the Y-curves are used to find the exit temperature of the water when the two parameters described in Eq. 2-6 and 2-7 are known. These parameters are listed again below:

$$\frac{KL}{c_w \rho_w Q} \tag{4-1}$$

$$\frac{h^2 t}{D^2} \tag{4-2}$$

where:

K = conductivity of concrete

L = length measure along the cooling pipe

c_w = specific heat of water (or other cooling fluid)

ρ_w = density of water (or other cooling fluid)

Q = cooling fluid flow rate

h = diffusivity of concrete

t = time since cooling commenced

D = diameter of the cooled cylinder

As the water absorbs heat from the concrete, it increases in temperature. Therefore, the concrete at the inlet end of the pipe is cooled more than the concrete near the exit because the water is cooler at the inlet than the outlet. However, the Bureau of Reclamation accounts for this by reversing the flow of water every twelve hours. Therefore it can be assumed that the rate of cooling of the concrete at all locations along the length of the pipe is relatively equal. The Y-curves can be used to determine the exit temperature of water since cooling has commenced and this value can be averaged with the inlet water temperature to get an average cooling water temperature for the pipe.

4.1.1 Incremental Analysis Procedure

An ABAQUS analysis is divided into steps that are divided into smaller time increments. At the beginning of each increment, it is possible to change a variety of conditions including the boundary temperatures. If the boundary temperatures are controlled by a subroutine, this subroutine is called at the beginning of each increment to recalculate the boundary temperature specified for the corresponding increment. As can be seen from Eq. 4-1 and 4-2, if the Y-curves are going to be used to calculate the exit temperature of the water, a variety of parameters need to be specified. The flow rate (*Q*), concrete conductivity (*K*), specific heat of water (c_w), density of water (ρ), and concrete diffusivity (*h*) are constant for a particular problem. The length of the cooled cylinder (*L*) is measured as the length of coil in a particular lift. This value and the diameter of the cooled cylinder (*D*) will change as the spacing of the coils and/or the lift size changes. The time (*t*) is the total time since the start of cooling.

As stated earlier, the Y-curves do not account for heat generation. This becomes a problem when trying to find the exit temperature. Once the Y-value is determined, Eq. 4-3 is used to determine the exit temperature.

$$\textit{Exit Water Temp.} = Y * (\textit{Intial Concrete Temp.} - \textit{Intial Water Temp.}) + \textit{Initial Water Temp.} \tag{4-3}$$

The initial (input) temperature of the water is known and the initial temperature of concrete is typically the placement temperature. Then, using the time since the start of the analysis, the exit temperature of the water at any time after the start of the analysis can be found. However, when heat generation is occurring in the concrete, this does not give an accurate result because heat generation was not included in the derivation of the Y-curves.

One way to deal with heat generation and the Boulder Canyon theory is to solve the problem in a series of small increments, where each increment is its own problem. The values at the end of one increment become the initial conditions for the next. Therefore, at the end of each increment the average concrete temperature is determined. This average concrete temperature is used as the placement (initial) temperature of concrete for the next increment. This solution should prove to be relatively accurate, except that the X, Y, and Z Boulder Canyon Theory developed in Chapter 1 was developed to use the time since the beginning of cooling at the time (*t*). The theory was not designed for an incremental solution, but can still be used reliably. The use of an incremental solution is necessary to account for the effects of heat generation. A flow chart depicting the method followed for the solution is shown in Figure 4-1.

Figure 4-1: *Incremental Procedure*

Increment 1

Boundary Temperature = (input water temperature + exit water temperature)/2

Concrete temperature at end of increment

→

Increment 2

Used as concrete placement temperature. New exit water temperature calculated. Average water temperature applied as new boundary temperature over this increment.

Use of the boundary temperature at cooling coil locations is implemented efficiently. It requires the use of two subroutines. One is DISP and the other is URDFIL. DISP is called at the beginning of each increment. The user inputs certain constants, such as the placement temperature of the concrete, the input temperature of the water, and the Y-values needed. DISP calculates the exit temperature of water for that particular increment based on the appropriate Y-value and the current temperature of concrete. After finding the exit temperature of the water, DISP averages the exit and inlet temperatures and produces the average temperature to be applied as the boundary temperature for that increment. Then this process is repeated at the beginning of the next increment. The subroutine URDFIL allows the user access to the ABAQUS results file during the analysis. The concrete node temperatures are stored in the results file, along with all other analysis data. The results file must be accessed by URDFIL in order to obtain the average concrete node temperatures at the end of the increment and the length of the time increment.

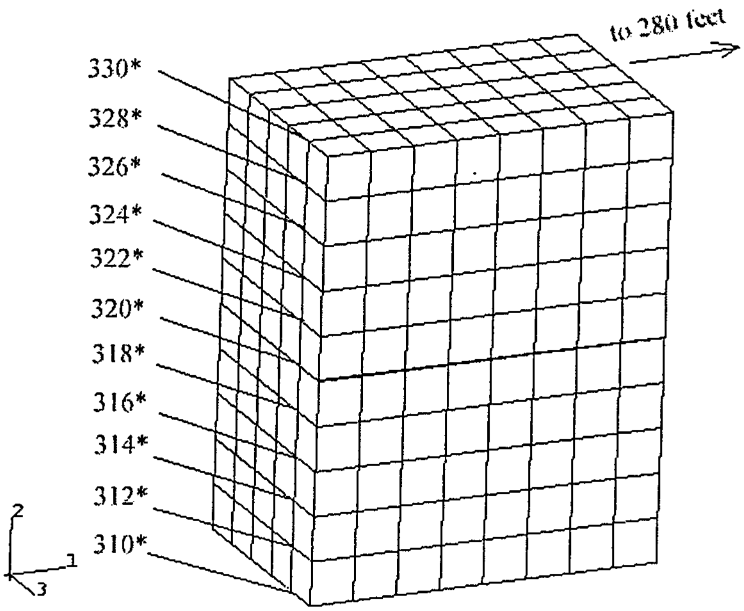
The necessary Y-values are based on the different lengths of coil and the time increments used in the analysis. The user must enter all the Y-values necessary throughout the analysis. The Y-values will change with the changing increment times and also as the size of the lifts, and therefore the coils, change. More detail on finding the appropriate Y-values is given in Chapter 6. The current temperature of concrete is taken as an average of two corner nodes at approximately 33.3% of the diameter of the cooled cylinder above and below the cooling coils. All cooling coil nodes in a particular lift are assigned the same average temperature concrete nodes because the temperature in the concrete should be relatively constant except for edge effects. Again, more detail on choosing the appropriate average concrete temperature nodes is given in Chapter 6.

4.1.2 Average Concrete Temperature Nodes

As demonstrated above, it is important to accurately determine the concrete temperature at the end of one increment to use as the placement temperature at the start of the next increment. Therefore, selection of the appropriate average concrete nodes impacts the exit temperature of water calculated from the placement temperature of the concrete as shown in Eq. 4-1. Since the placement temperature of concrete becomes the average concrete temperature at the end of the previous increment, incorrect selection of this node could lead to inaccurate results. The X-values developed during Boulder Canyon are used to determine the mean concrete cylinder temperature. An ABAQUS 3D analysis was completed for a straight 280' foot coil and the temperatures at the nodes surrounding the cooling coil were plotted.

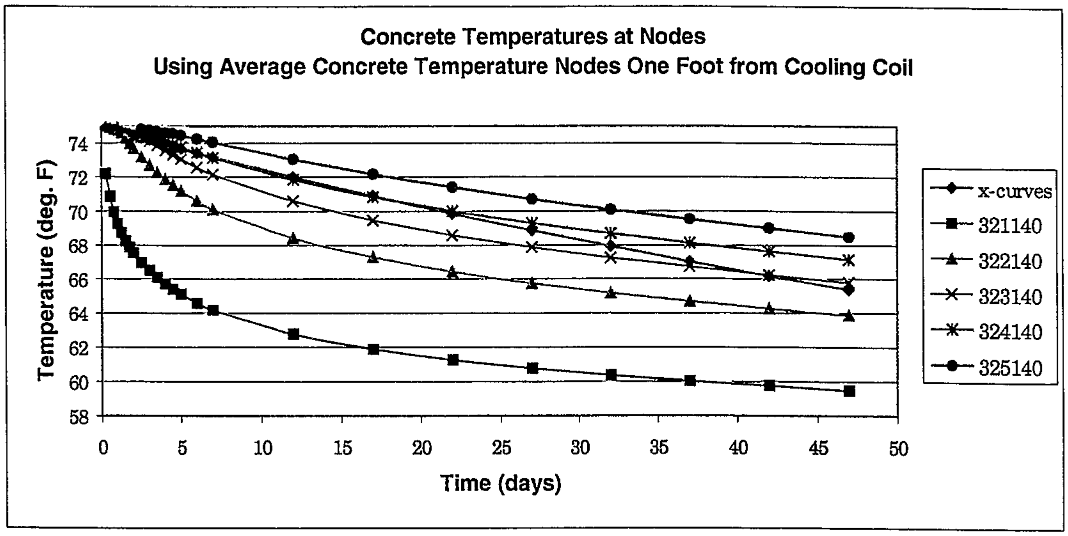
The analysis was completed without including heat generation because the X-charts do not account for heat generation. As shown in Eq. 4-1, the exit water temperature of water is dependent on the average concrete temperature at the end of the increment. Therefore, several nodes were used to calculate the average concrete temperature. The nodes were corner nodes and had increasing radial distances from the cooling coil. The model is similar to the one shown in Figure 3-3, except that the coil is 280' long in the '1' direction, instead of 16' long as shown in Figure 3-3. A drawing of the node numbers is shown in Figure 4-2.

Figure 4-2: *Node Numbers for 280' 3D Mesh*



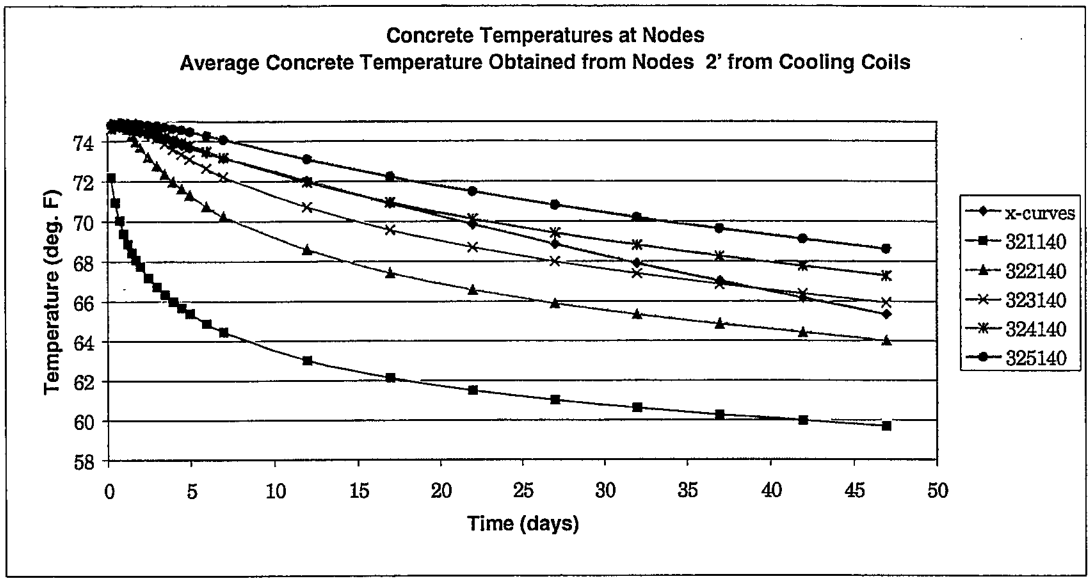
The '*' is the portion of the node number related to the location of the node in the '1' direction. For example, the nodes of the very left end of the 280' model would have a '*' of '000' (ie. 312000). The nodes at the halfway point are located 140' down the coil and have a '*' value of '140' (ie. 312140). The nodes numbered in Figure 3-10 are corner nodes. Between each two nodes shown is a midnode. This midnode has a number designation between that of the two corner nodes (ie. the midnode between corner nodes 310140 and 312140 is 311140). The 280' long cooling coil was placed in the plane of node 320140 which is the plane of intērface between lift 1 and lift 2. The first model results are shown in Figure 4-3. This model used nodes 321140 and 319140 as the two average concrete nodes.

Figure 4-3: *280' 3D Model Using Nodes 1' Away As Concrete Temperature*



The concrete temperatures at the corresponding nodes above and below the coil are equal to one another. Therefore, Figure 4-3 shows only the temperatures in Lift 2. The lowest curve, 321140, shows the node temperatures one foot from the coil. Each line thereafter shows the concrete temperature at progressively increasing distances in one-foot increments. Therefore, 325140 is the furthest node from the cooling coil plotted, at five feet away. The line labeled 'X-curves' is the result obtained when the result is calculated by hand using the Boulder Canyon X-curves to find the mean concrete temperature. Figure 4-3 demonstrates that a node one foot away is a poor choice for the average concrete temperature because the curve 321140 does not match up with the 'X-curve' mean temperature. The result when nodes 322140 and 318140 are used as the two average concrete nodes is shown in Figure 4-4.

Figure 4-4: 280' 3D Model Using Nodes 2' Away As Concrete Temperature



This graph demonstrates that using average concrete nodes 2' away from the cooling coil is also not the best choice because line 322140 does not match the 'X-curves' mean temperature line. Figures 4-5, 4-6, and 4-7 show the results using average concrete nodes 3', 4', and 5' away respectively.

Figure 4-5: *280' 3D Model Using Nodes 3' Away As Concrete Temperature*

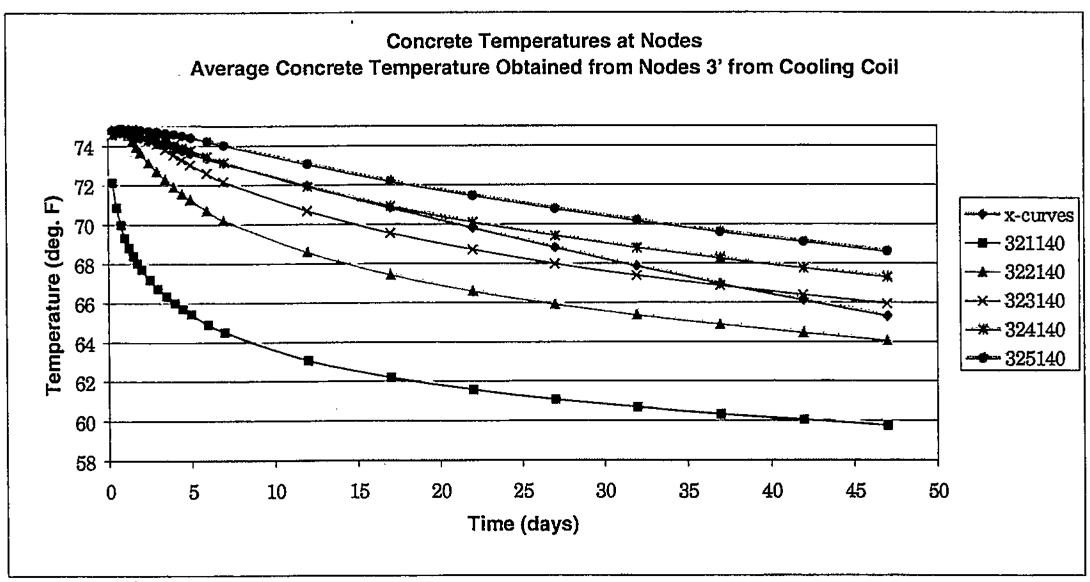


Figure 4-6: *280' 3D Model Using Nodes 4' Away As Concrete Temperature*

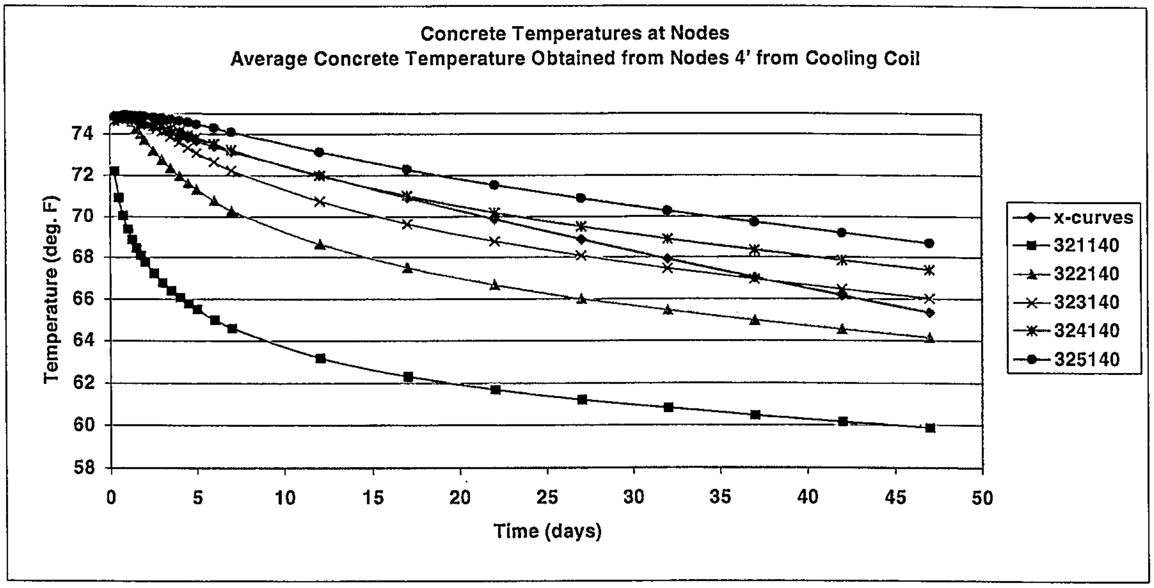
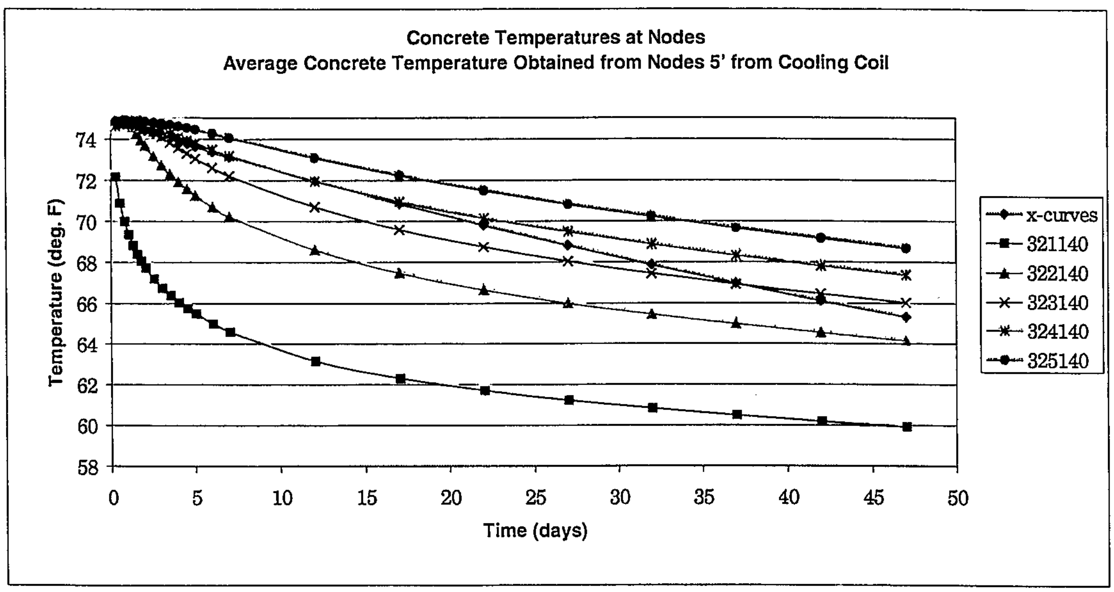
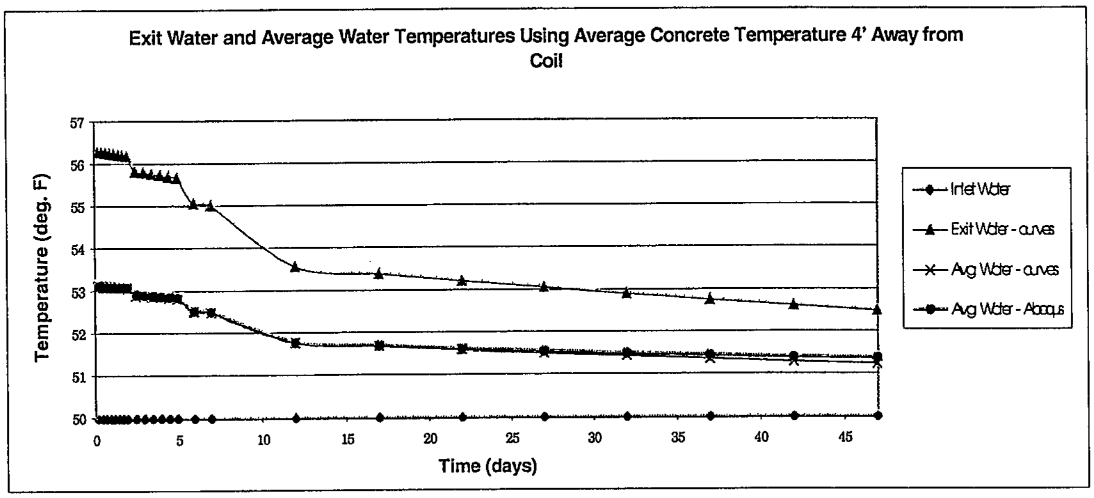


Figure 4-7: *280' 3D Model Using Nodes 5' Away As Concrete Temperature*



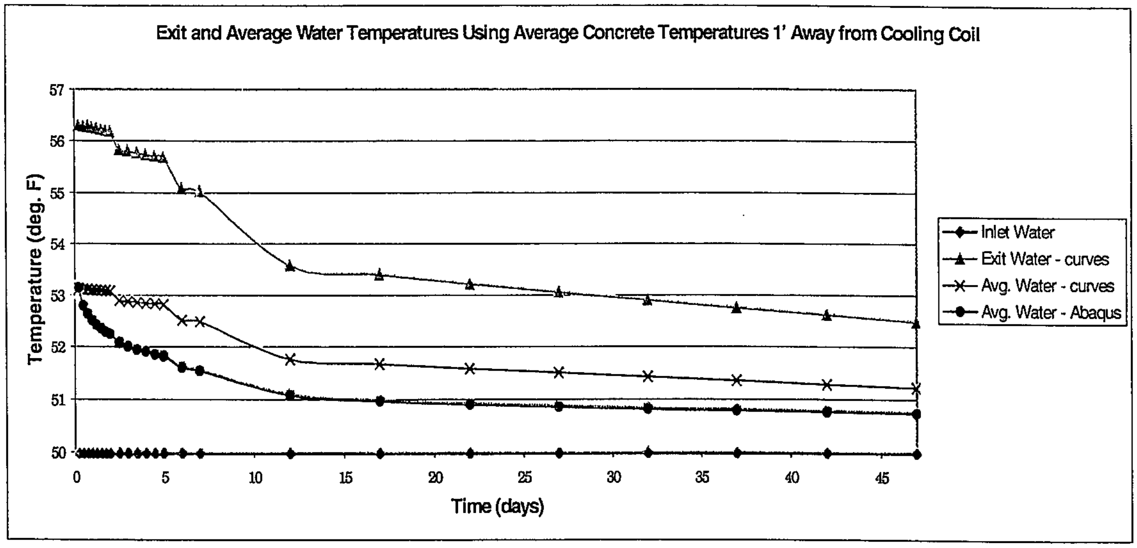
From these three graphs, it can be determined that the mean concrete temperature given by the 'X-curve' line is best represented by the concrete temperatures 3' and 4' from the cooling coil. This is demonstrated by the curves because the 3' and 4' node spacings in their respective graphs most closely correspond to the X-curves temperature value. The spacing of the coil in this model is 10'Vx10'H. Using Table One, the diameter of the cooled cylinder corresponding to this spacing is 11.28'. Thus, 3' and 4' radial distances correspond to 26.6% and 35.5% of the diameter respectively. This leads to the recommendation to use the closest corner node to 33.3% of the cooled cylinder diameter. It is also important to note that variations in the choice of the node only marginally impact the resulting average boundary temperature. This can be demonstrated by the following two graphs. The difference between using a concrete node 4' away as the average, which is quite accurate, and a concrete node 1' away as the average, which is not accurate, is inconsequential as shown in Figures 4-8 and 4-9.

Figure 4-8: *Average Boundary Temperature Using Nodes 4' Away As Concrete Temperature*



This graph displays several lines that are not smooth, but instead have steps. These steps will be discussed in more detail below. The first line plotted is the inlet water temperature (which remains constant). The exit water temperature is determined by hand using the X and Y-curves. The exit water temperature is averaged with the input water temperature to obtain the average water temperature-curves. The 'avg water-abaqus' line displays the ABAQUS result obtained using the average concrete temperature from the chosen nodes. In the case of Figure 4-8, they are nodes 4' away from the coil. As described above, the 4' radial nodes are good approximations for the average temperature of concrete. This is observed by the proximity of the 'Avg Water-curves' and 'Avg Water-Abaqus' lines. This effect is not seen when nodes 1' away are used for the average concrete temperature, as shown in Figure 4-9.

Figure 4-9: *Average Boundary Temperature Using Nodes 1' Away As Concrete Temperature*



However, even though the 'Avg Water –curves' and Avg Water – Abaqus' lines for the 1' average concrete nodes solution do not line up nearly as well as in Figure 4-8, the difference is about 1°F. Figure 4-3 shows that the 1' concrete node temperatures are about 9°F from the average concrete temperatures as determined by the X-curves. However, this only translates to about a 1°F difference in average water temperature. This water temperature then impacts the calculated concrete temperatures for the next increment only marginally. This is important because the primary concern is obtaining accurate concrete temperatures. Therefore, using the closest corner node to (33.3%) is accurate enough for most purposes.

4.1.3 Incremental vs. Total Time Analysis

The last important issue to be addressed with the boundary solution is the steps seen in the water temperature as demonstrated by Figures 4-8 and 4-9. These steps illustrate a very important point – that the curves developed during the Boulder Canyon Dam investigation are not meant to be used to solve an incremental analysis. This means that the *t* value in Equation 2-7 is supposed to be the total time since the start of cooling, as stated earlier. However, since the curves do not include heat generation, it is impossible to incorporate heat generation into the solution without using the incremental solution described above, where each time period is solved as its own small problem, and the ending parameters from one increment are used as the initial values for the next. When using ABAQUS, these time increments can be changed throughout the analysis. When the time increment changes, the Y-value used changes because the t value in Eq. 2-7 changes. This is why the user is required to enter a new Y-value for the different time increments, as mentioned earlier. At each Y-value change, a jump is seen in the exit temperature values found using Eq. 4-1. These are the jumps seen in Figures 4-8 and 4-9.

To analyze the error in the solution when an incremental solution is used instead of a total time solution, the problem without heat generation was solved several different ways. Using a 280' straight coil, 3D model with 10' x 10' lift spacing and no heat generation the problem was solved using ABAQUS. Two types of ABAQUS analysis were completed. The first was a total time analysis. The Y-values used changed for every increment as the total time increased. The only difference between solving the analysis using ABAQUS in this manner vs. completing the analysis by hand, is that ABAQUS calculates the concrete temperatures. Otherwise the concrete temperatures would need to be found using the X and Z-charts. For the incremental analysis, the procedure was the same as that described above. The analysis was completed in ¼ day increments which is considered to be the minimum increment specified by the Army Corp of Engineers for NISA models. The average concrete temperature was based either on nodes 3 feet away (Figure 4-10) or nodes 4 feet away (Figure 4-11).

Figure 4-10: *Total Time vs. Incremental Analysis: ABAQUS Incremental Temperatures Based on Average Concrete Nodes Three Feet Away*

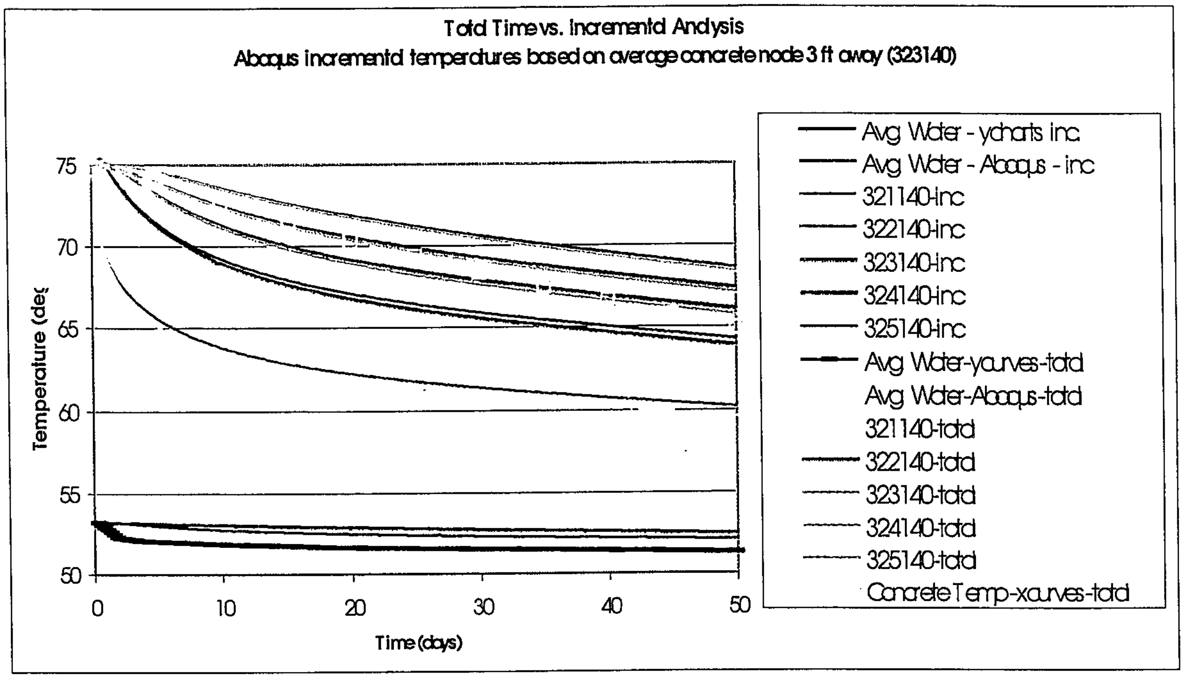
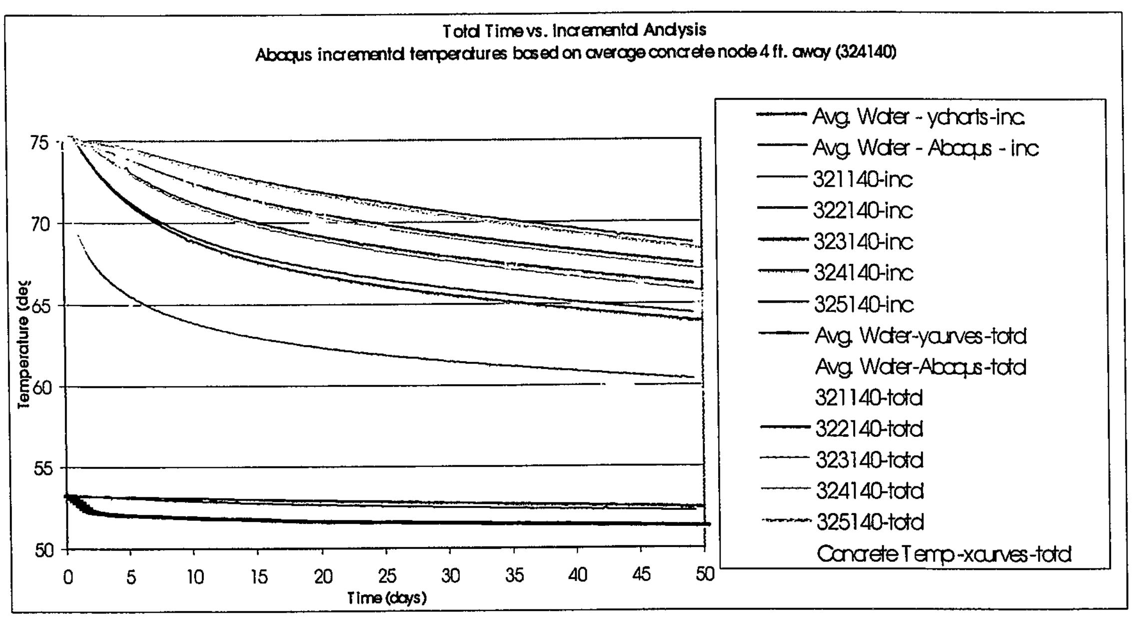


Figure 4-11: *Total Time vs. Incremental Analysis: ABAQUS Incremental Temperatures Based on Average Concrete Nodes Four Feet Away*



Both Figure 4-10 and 4-11 are essentially the same, again demonstrating the insignificant difference made by the choice of the average concrete nodes as long as they are close to the correct values as predicted by the X-curves. The nodes numbers 321140, 322140, 323140, 324140, and 325140 signify concrete nodes at 140' along the length of the coil and at 1', 2', 3', 4', and 5' radial distances away from the cooling coil respectively. The two curves 'Avg. Water-ycurves-total' and 'Avg. Water-Abaqus-total' are the average of the inlet and exit water temperatures from a hand calculation analysis using the Y-curves and the ABAQUS result respectively. Only one curve is visible because the curves are the same and plot on top of one another, which is expected. The two curves 'Avg. Water – ycharts – inc' and 'Avg. Water – Abaqus – inc' are the average water temperatures determined with an incremental analysis from a hand calculation analysis using the Y-curves and the ABAQUS results respectively. The slight difference in these two curves is due to the difference in the average concrete node chosen in ABAQUS ('323140-inc.' or '324140 – inc.') vs. the X-curve average concrete value 'Concrete Temp – xcurves - total'. Again, it can be seen the difference in the average water curves is slight. Of most importance is the error between the average water temperatures calculated using the incremental or the total time analysis. These values have a maximum difference of 1.3° (Figure 4-10). This is not necessarily insignificant, however it leads to very small differences in the concrete temperatures which is what is ultimately the most important. The concrete temperatures plotted at each node for the incremental and total time analysis plot right next to one another, with the most discrepancy seen at the node closest to the cooling coil, 321140. This difference has a maximum value of 0.52°. Therefore, it is concluded that the error incurred in the concrete temperature results by using incremental analysis techniques instead of total time analysis is minimal.

4.2 Summary

The boundary node method for modeling the cooling coils has several advantages, and also disadvantages. A major advantage of using the boundary method of modeling the cooling coils is that it is easily implemented into an existing model. No change of the mesh is required, and no special mesh, element size, or node placement is required to use the procedure. The actual mechanics of implementing the procedure into a model are outlined in Chapter 6. However, the implementation is not rigorous, and requires no subroutine modification by the user beyond entering certain parameters such as Y-values, placement concrete temperature, and input water temperature. Also, implementation is essentially the same in the two-dimensional and three-dimensional analysis, reducing confusion for the user.

The two-dimensional model would be most likely used to try a variety of cooling coil spacings and designs. It is easy to modify the cooling coil spacings as long as the user has nodes placed where they would like to place coils. In addition, the three dimensional model can accommodate any winding pattern for the cooling coils layout. Another important point to mention, which will be discussed again in Chapter 6, is that the model does not require that the cooling coils be functional for the duration of the analysis. The coils can be turned on for any steps in the analysis, then turned off when the user would like to stop cooling. They can also be turned back on later in the analysis if desired by the user.

The most important disadvantage to the boundary node method of modeling the cooling coils is the reliance on the Y-curves. The Y-curves were developed based on several assumptions, including an insulated cylinder, a straight coil, and non-incremental analysis. However, the curves have been used extensively by the Bureau of Reclamation since the construction of the Hoover Dam, with good results. In addition, as has been established, the error due to an incremental analysis is minor. However, a method of analysis which does not require the use of the Y-curves would be desirable.

The other disadvantage of using boundary nodes to model the coils is that the coils must be placed at node locations. Due to this constraint, the user should consider possible spacing options before creating their mesh in order to choose a node spacing which allows for analysis of several coil spacing options.

Chapter 5

Results of Boundary Temperature Model

This chapter will demonstrate the results of the cooling coil model implemented in actual dam systems. The chapter begins with simplistic representative problems that demonstrate the effectiveness of the model, both in 2D and 3D. The last model presented is the 2D Portuguese Dam model from the Army Corp of Engineers.

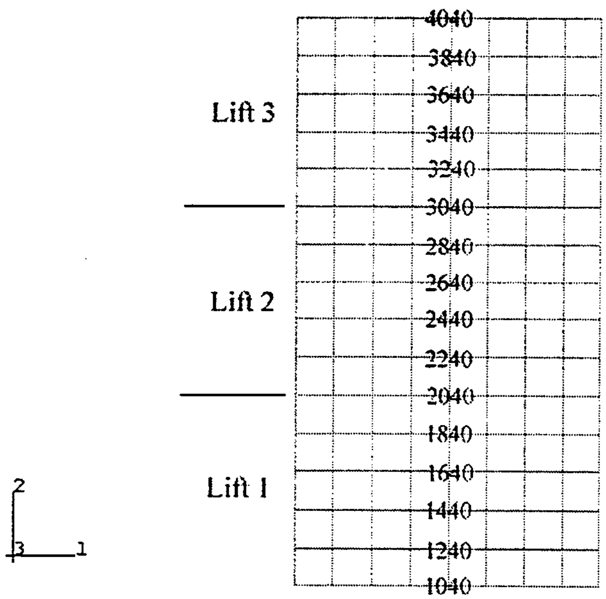
5.1 Preliminary Results

First, a two-dimensional model will be presented. This model includes the sequential placement of lifts, films, heat generation, and other 'real life' parameters. Then, an example 3D model will be presented in less detail. Finally, two models will be presented which demonstrate the compatibility of the 2-dimensional and 3-dimensional results.

5.1.1 Two-Dimensional Model Results

To demonstrate the model results, a 2D model is presented below. This model has three 10'V x 16'H lifts placed sequentially in seven day increments. Film coefficients surround the boundaries of the lift exposed to the air. The film coefficients are modeled with the amplitude ambient temperature for the Portuguese Dam. The base of the first lift has a symmetry boundary to represent the interface with the foundation, which is very conservative. Heat generation is included in all three lifts, with the amount of heat generated dependent on the time since the lift has been placed. Heat generation is controlled by the subroutine HETVAL. Figure 5-1 represents the element configuration of the model, and indicates certain node numbers on a vertical line through the center of the model. The temperatures at these node locations will be used to later to plot temperature distributions in the model, so it is important to note their placement in the model.

Figure 5-1: *Two-Dimensional, three lift model*



This model begins with the first lift being placed on day one, the second on day 7, and the third on day 14. The model was run for 421 days. The increment time varied, with smaller increments being used for the beginning portion of the analysis when heat generation was occuring, and larger increments being used as the temperature became more constant. The cooling coils were controlled by the boundary command and the subroutines DISP and URDFIL as described in Chapter 4. Three cooling coils were placed at four feet intervals at the interfaces between the lifts. The cooling coils were not activated until the upper lift bordering the interface was placed. Figure 5-2 shows the temperature contour after 1.25 days when only one lift is in place and no cooling coils have been activated. The placement temperature of the concrete at day 0 was 75°.

Figure 5-2: *Three Lift, 2D Analysis after 1.25 days*

(Scale: maximum 100°F, minimum 90.8°F, interval 0.7°F)

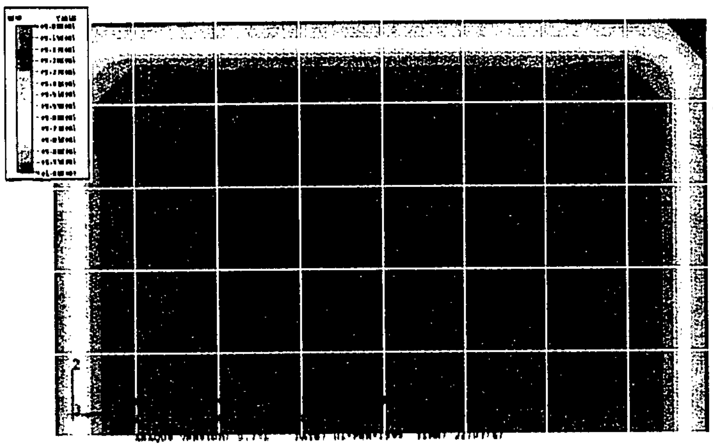


Figure 5-2 shows that the maximum temperature reached after 1.25 days due to heat generation is 100 degrees. The coolest temperature is about 91° at the three boundaries being cooled by the ambient temperature. Again, the bottom edge of the lift (which would be the interface with the foundation in an actual dam) has a symmetry boundary. Figure 5-3 shows the model at time 7.25 days; 0.25 days after lift two has been placed. The cooling coils between lift one and two were activated when lift two was placed at day 7.

Even after 0.25 days, the cooling of the concrete by the coils is visualized. The maximum temperature in lift one is 117°. The temperature in lift 2 is roughly 80°. Lift 2 had a placement temperature of 75° and has been experiencing heat generation for only 0.25 days. The cooling coils at the interface between lift 1 and lift 2 shown here are at a temperature of 51.6°. This temperature is calculated as discussed in Chapter 4 by subroutines 'DISP' and 'URDFIL' using an input water temperature of 40°. The average concrete nodes used are 2240 and 1840 (see Figure 28). Nodes 2240 and 1840 are at 2' from the cooling coil. The diameter of the cooled cylinder for 10'V x 4'H cooling coil spacing is 7.14' (Table 1). Following the guidelines for choosing the correct average concrete nodes as detailed in section 4.1.2, we have a choice between corner nodes 2' or 4' from the coil. This leads to 28% and 56% of the diameter respectively. Therefore, nodes 2' away were the best choice. They are chosen in the center of the lift to avoid end effects. The same cooling coil temperature is applied to all three coils since in the actual problem this would be the same coil twisting through the lift. The exterior boundaries are cooled by the ambient temperature. The contours caused by cooling due to the coils can begin to be seen at this point. They more pronounced in Figure 5-4, after 13 days.

Figure 5-3: *Three Lift, 2D Analysis after 7.25 days*

(Scale: maximum 117°F, minimum 51.7°F, interval 5°F)

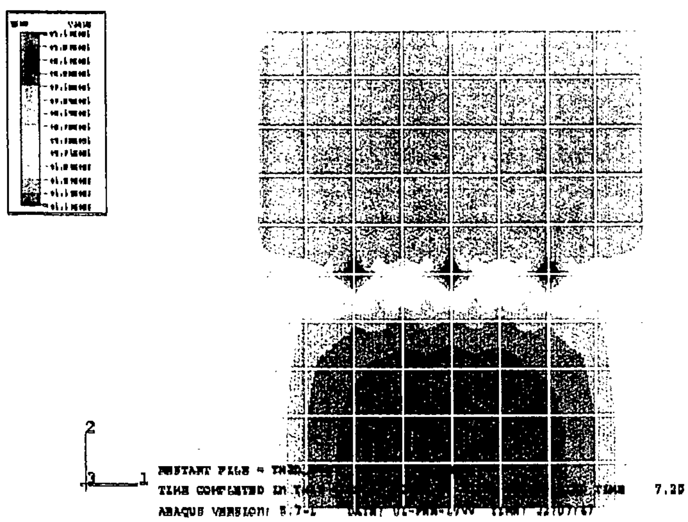
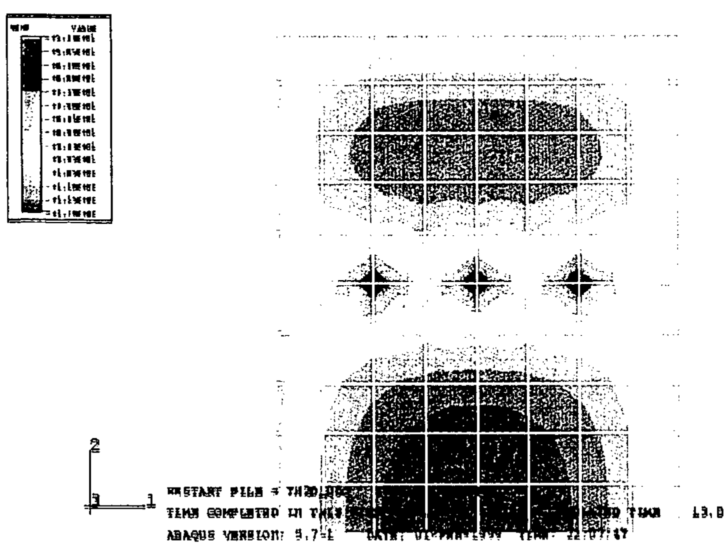


Figure 5-4: *Three lift, 2D Analysis after 13.0 days*

(Scale: maximum 120°F, minimum 53.4°F, interval 5.1°F)



In Figure 5-4, the effect of the cooling coils can be clearly seen. Their action is to cool the center portion of the model. The highest temperature experienced is close to the symmetry boundary, at 120°. The maximum temperature experienced in lift 2 is about 110°. The area close to the cooling coils is 85 to 90°F. The cooling coil temperature at this point is 53.4°. It is almost 2° higher than the cooling coil temperature at 7.25 days because the temperature of the average concrete nodes is increasing due to heat generation. At day 14, lift 3 is placed. Figure 5-5 shows the model at time 14.25 days, 0.25 days after lift 3 has been placed.

Figure 5-5: *Three Lift, 2D Analysis after 14.25 days*

(Scale: maximum 120°F, minimum 51.6°F, interval 5.25°F)

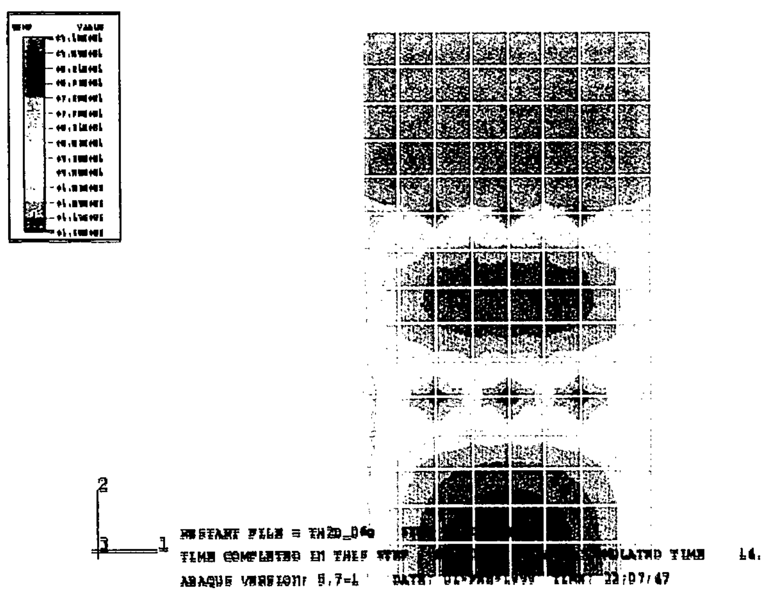
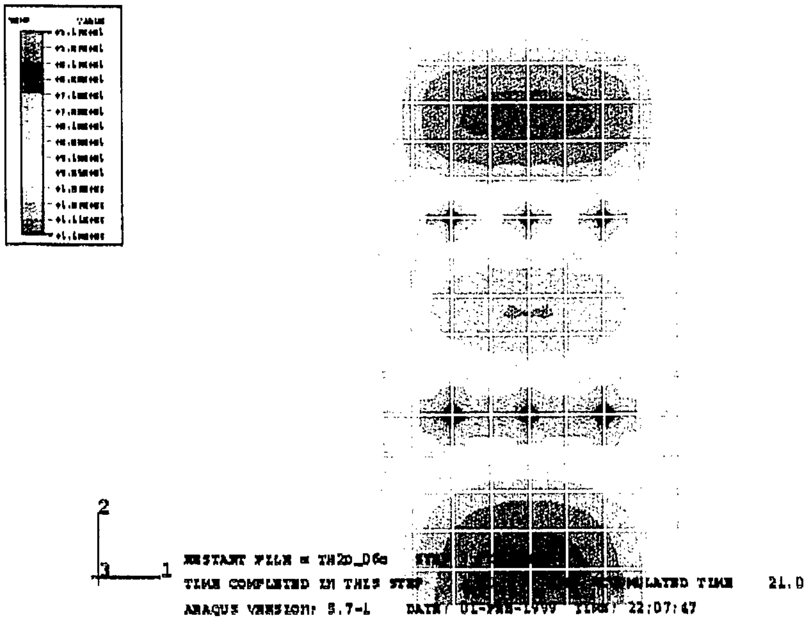


Figure 5-5 shows the model with lift 3 in place. Lift 3 is initially much cooler than lifts 1 and 2 because it has only been generating heat for 0.25 days. The cooling coils are activated between both lifts one and two and lifts two and three. The coils at the interface between lift two and three use 3240 and 2840 (see Figure 28) as the two average concrete nodes for the same reasons described above for nodes 2240 and 1840. The cooling coils at the interface between lift 1 and 2, and lifts 2 and 3 can be at different temperatures because their average concrete nodes are at different temperatures. The difference will become less pronounced as the heat generation ceases and the concrete temperatures became more evenly distributed throughout the model. The contours after 21.0 days are shown in Figure 5-6.

Figure 5-6: *Three Lift, 2D Analysis after 21.0 days*

(Scale: maximum 116°F, minimum 51.7°F, interval 4.95°F)



In Figure 5-6, the cooling from the coils is clearly visualized. The difference in the progression of the cooling at the interface between lifts 1 and 2 compared to lifts 2 and 3 is also clear. The highest temperatures experienced at this point are at the symmetry boundary in lift 1, and in the center of lift three. Lift two is being cooled by cooling coils on either side. At day 41, the extent of cooling in lift 2 is even more pronounced, emphasizing the effect that the cooling coils have on the model as shown in Figure 5-7.

The center of lift two in Figure 5-7 is at about 80° at this point. This contrasts with the maximum temperature of 99.7° at the symmetry boundary, which is experiencing little cooling from either the coils or the ambient temperature. The maximum temperature in lift 3 is about 91°. After 421.0 days, the model has cooled to the point that the ambient temperature is higher than the concrete and the external temperature is actually heating the sides of the model. This is seen in Figure 5-8.

Figure 5-7: *Three-Lft, 2D Analysis after 41.0 days*

(Scale: maximum 99.7°F, minimum 48.8°F, interval 3.9°F)

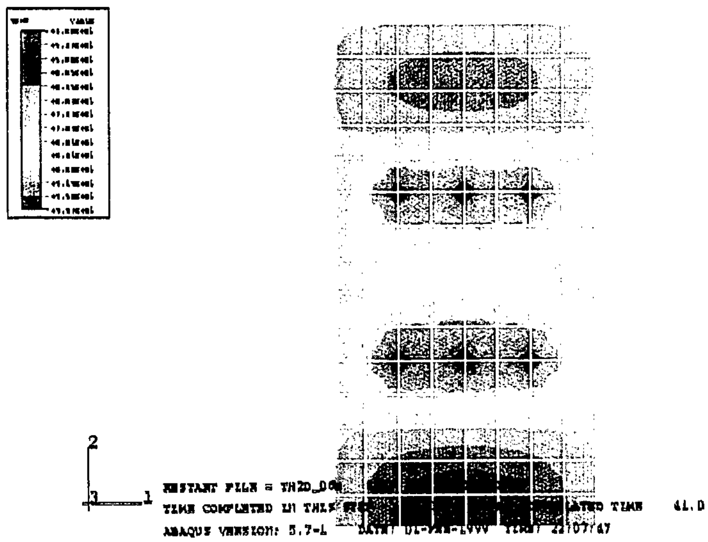
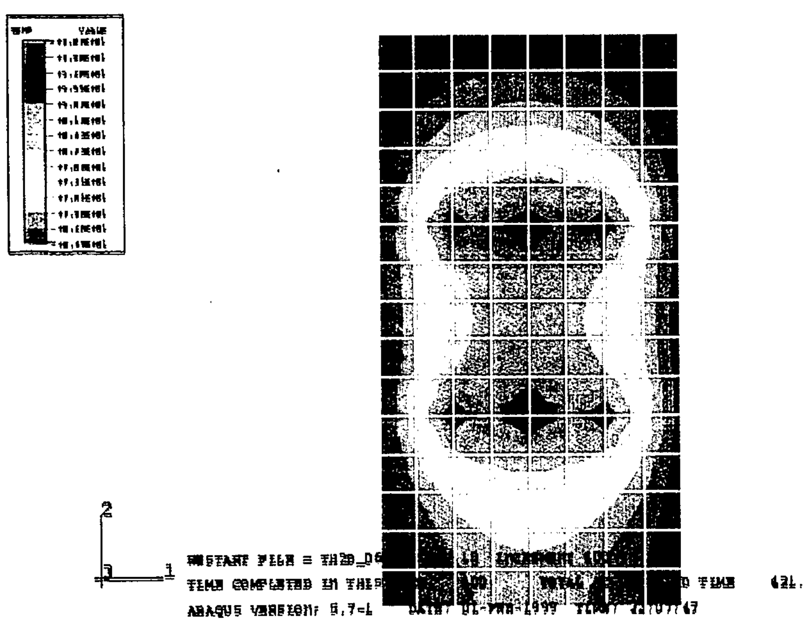


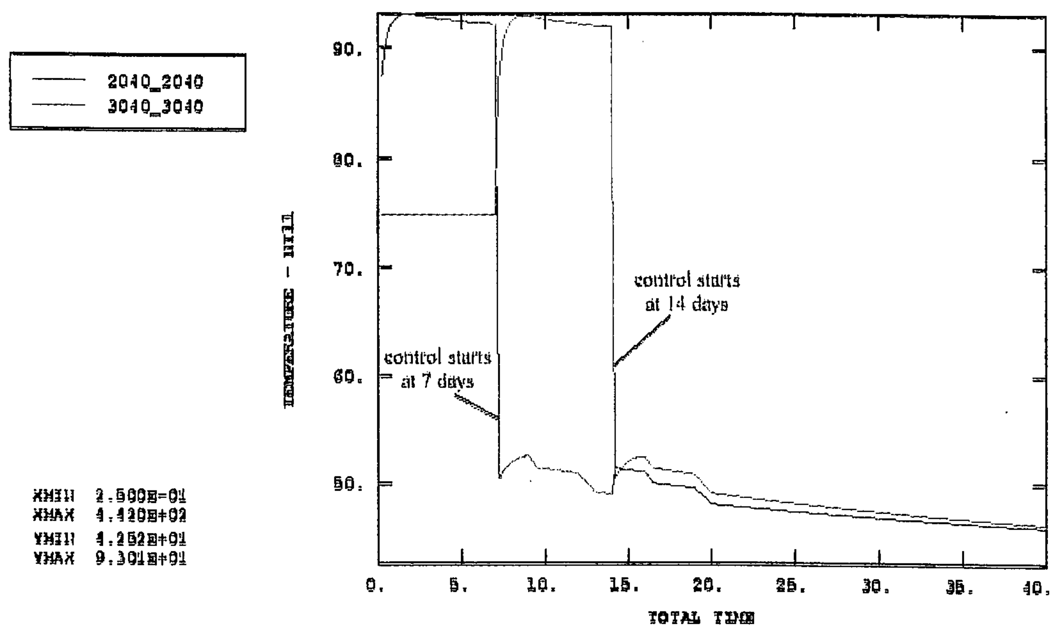
Figure 5-8: *Three Lift, 2D Analysis after 421.0 days*

(Scale: maximum 84.9°F, minimum 46.7°F, interval 2.9°F)



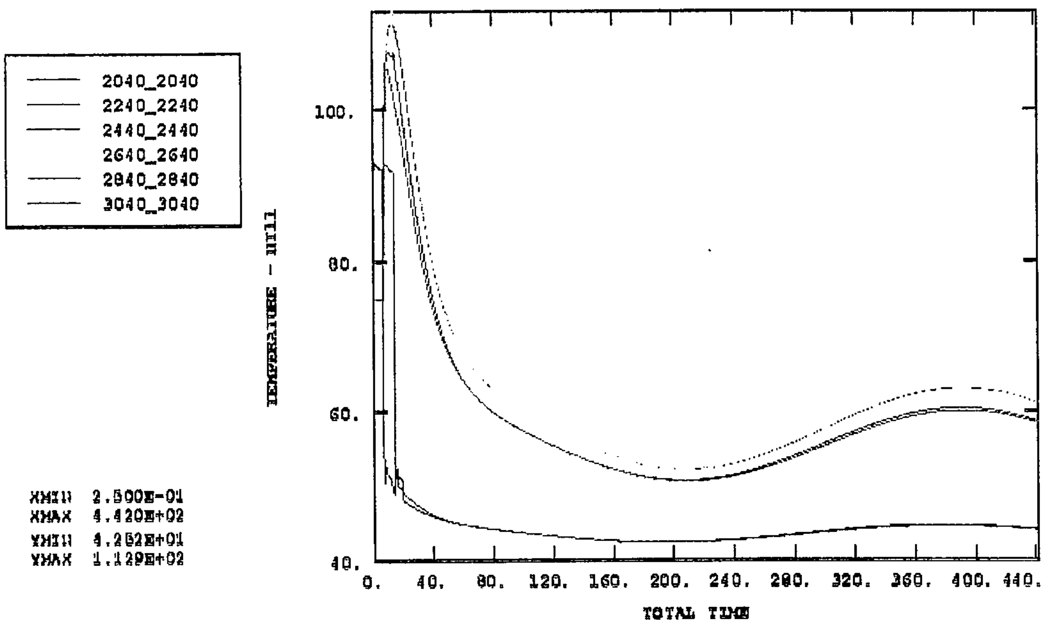
The temperature in the center of the model is about 67°, demonstrating the extent of cooling possible by the coils. The boundary temperature is about 85° around all three sides due to the ambient temperature. The progression of cooling is more clearly seen when the node temperatures are plotted over time. Figure 5-9 shows the cooling coils temperatures at the interface of each lift by plotting cooling coil nodes 2040 and 3040 over time.

Figure 5-9: *Three Lift, 2D Model : Cooling Coil Temperatures*



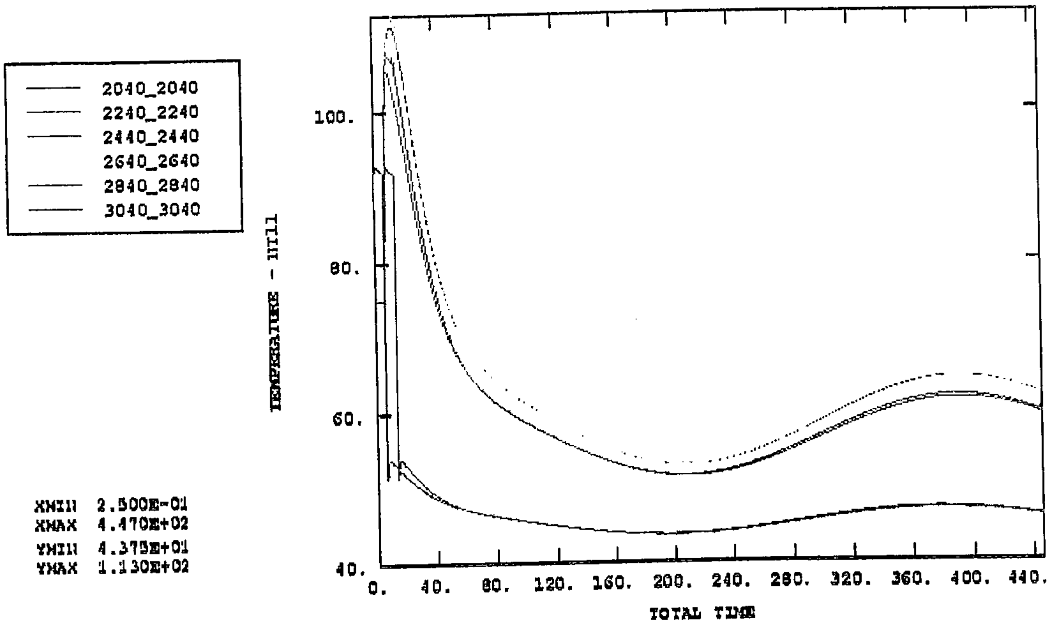
The node number of the cooling coil is given in the box on the upper left of Figure 5-9. The steps viewed in the lower part of both curves are due to the changing Y-values discussed in 4.3.1. For the first seven days, the node 3040 does not exist in the model because lift 3 has not been placed. Therefore ABAQUS plots the 75° placement temperature for node 3040 for the first 7 days. At day 7, lift 2 is placed, and the node becomes active. For both coils, during the first seven days of their placement they function as normal concrete nodes. They experience heat generation, obtaining a maximum temperature of 93.0°. After they have been in place for 7 days, the lift above them is placed, and they are abruptly turned to cooling coils controlled by subroutines DISP and URDFIL as described in Chapter 4. After heat generation ends and the concrete temperatures throughout the model become more constant, the cooling coil temperatures begin to level out, and are almost equal at day 140. The cooling coil temperatures compared to the concrete temperatures for lift two are viewed in Figure 5-10.

Figure 5-10: *Three Lift, 2D Model: Lift 2 Temperatures*



The node number given in the upper left corner of Figure 5-10 correspond to the node numbers in Figure 5-1. The two cooling coils 2040 and 3040 are the same as shown in Figure 5-1 as well. The peak concrete temperatures are affected by the node proximity to a cooling coil. The maximum temperature reached was 112.9° at node 2640. The oscillations that can be seen in the later part of the curve (after day 80) occur because the overall concrete temperature has reduced to the point that it now oscillates according to the ambient temperature. The same plot was created for a model with a constant Y-value instead of the correct, changing Y-values which lead to steps in the cooling coils temperature. This plot is shown in Figure 5-11.

Figure 5-11: *Three Lift, 2D Model: Lift 2 Temperatures with Constant Y-value*



The maximum concrete temperature reached at node 2640 using a constant Y-value is 113.0°. This differs from the 112.9° temperature found when using the correct, changing Y-values in Figure 5-10. This again demonstrates that the error incurred by the use of an incremental analysis with changing Y-values is minimal. The temperature plot for lift 1 (with the correct, changing Y-values) is shown in Figure 5-12.

The maximum temperature in lift 1 is 119.9°, reached by node 1040 which is on the symmetry boundary. From this upper boundary, we see a decreasing temperature experienced by each node as we progress toward the cooling coil (ie. 1240, 1440, etc.). Again, we see the oscillations in the later parts of the curve due to the ambient temperature. The lift 3 concrete temperatures are shown in Figure 5-13.

Figure 5-12: *Three Lift, 2D Model: Lift 1 Temperatures*

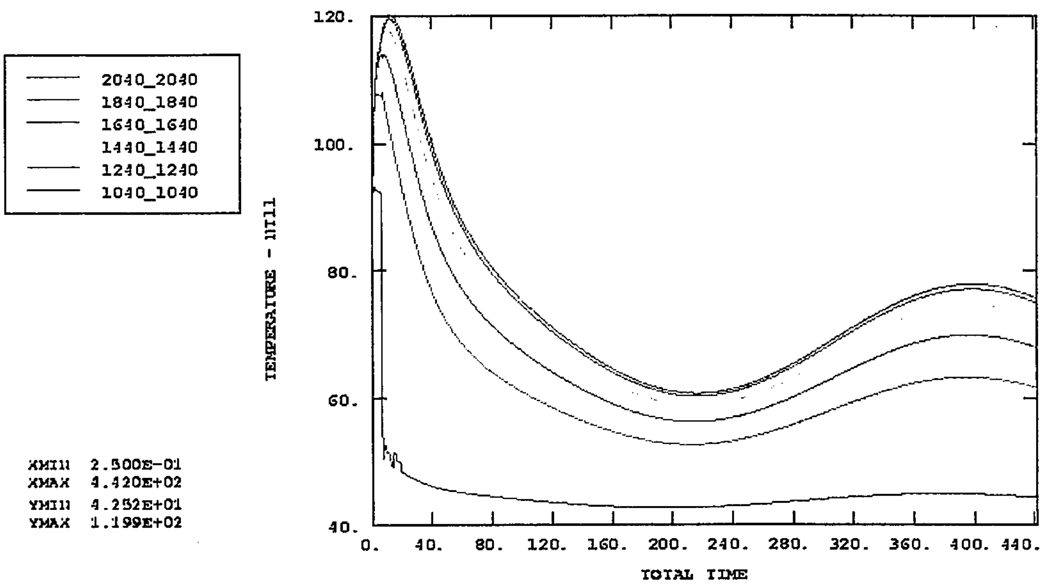
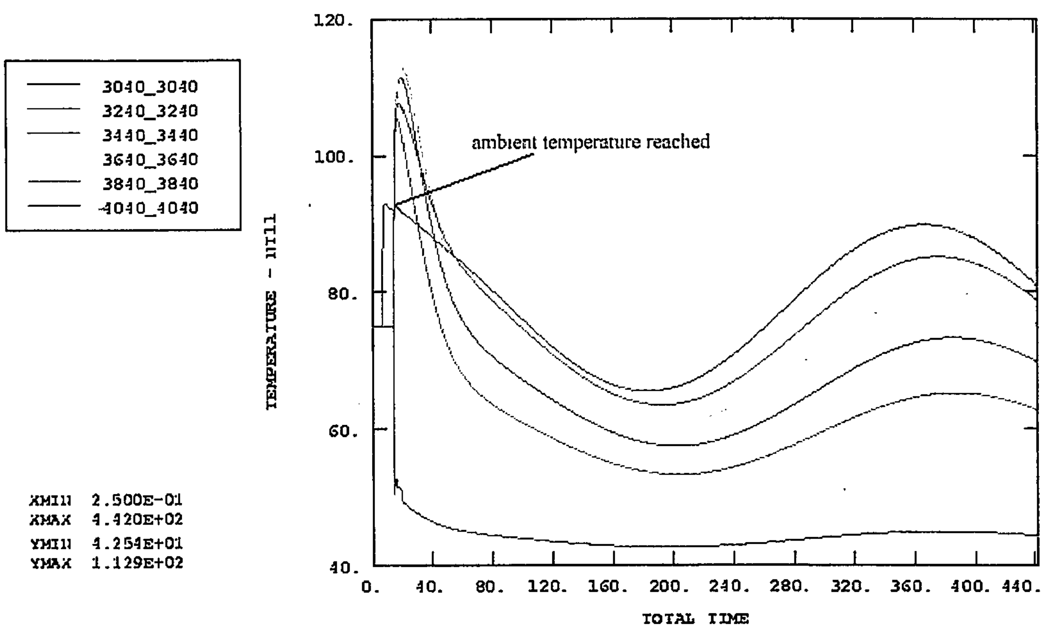


Figure 5-13: *Three Lift, 2D Model: Lift 3 Temperatures*



The maximum temperature reached in lift 3 is 112.9° by node 3640. However, in lift 3, the effects of the ambient temperature are clearly seen. Node 4040, which is sitting on the ambient boundary (see Figure 5-1), never reaches a maximum temperature close to those experienced by the interior portions of the lift. This occurs because the boundaries increase in temperature until they reach the ambient temperature, at which point they begin to follow the ambient temperature curve as they are cooled (or heated) by the external temperature. This effect is also seen at node 3840 whose peak is diminished by ambient temperature cooling. The peak temperature for node 3240 is strongly affected by cooling due to coil 3040.

5.1.2 Three-Dimensional Model Results

A three-dimensional model is demonstrated here in less detail to present the ease of modeling a variety of cooling coil patterns in three dimensions. The model presented is a three dimensional 10'Vx16'Hx10'D model with two lifts, both in place at the start of analysis. The model has ambient temperatures applied at the right and left faces, and symmetry boundaries on the bottom, top, front, and back faces of the two lifts. In the figures shown, the upper lift is removed so that the temperature distribution can be easily seen. The model includes a cooling coil that enters on the back face, winds through the model, and exits on the front face. Heat generation was included, with the initial water temperature at 50° and the concrete placement temperature at 75°.

Figure 5-14 shows a maximum temperature of 106° after 1.75 days. The cooling coil water is 51.6° and cooling due to the coils is apparent. The ambient temperature has cooled the left and right faces to approximately 91°. Close to the cooling coils, concrete temperatures are closer to 76°. The contour plot after 7 days is shown in Figure 5-15.

Figure 5-14: *3D Analysis After 1.75 Days*

(Scale: maximum 106°F, minimum 51.6°F, interval 4.2°F)

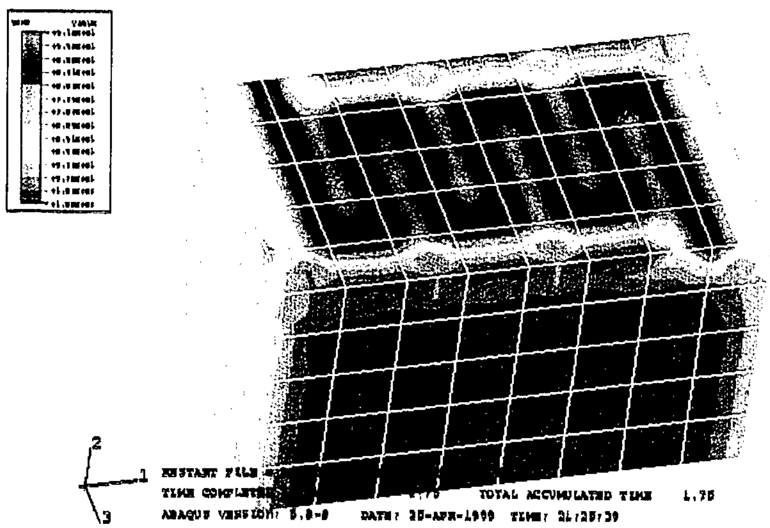
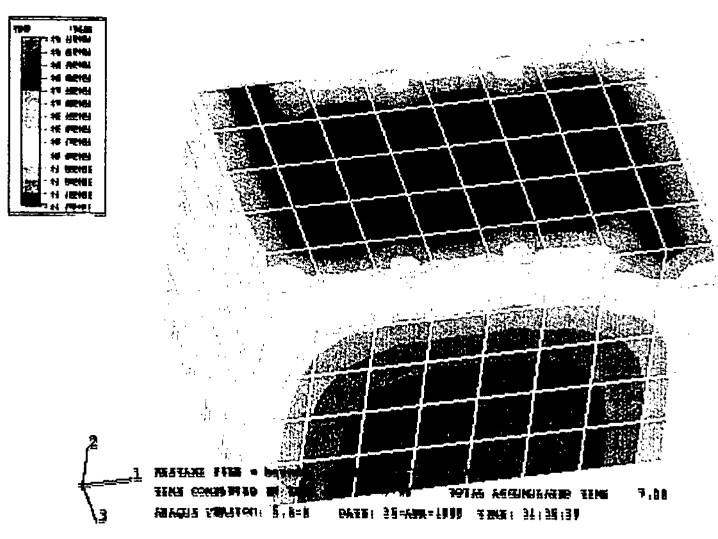


Figure 5-15: *3D Analysis After 7.0 Days*

(Scale: maximum 117°F, minimum 51.4°F, interval 5°F)



After seven days, cooling is more apparent. The faces with ambient temperatures applied are close to about 88°, and near the cooling coil concrete temperatures are about 75°. The maximum temperature in the lift is 117° at the bottom symmetry boundary and the cooling coil water is 51.4°. More extensive cooling is seen at days 107 and 257 shown in Figures 5-16 and 5-17.

Figure 5-16: *3D Analysis After 107.0 Days*
(Scale: maximum 74.1°F, minimum 50.3°F, interval 1.8°F)

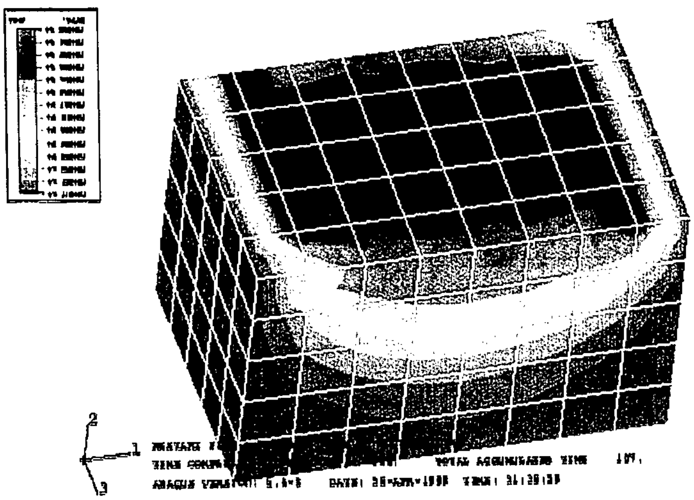
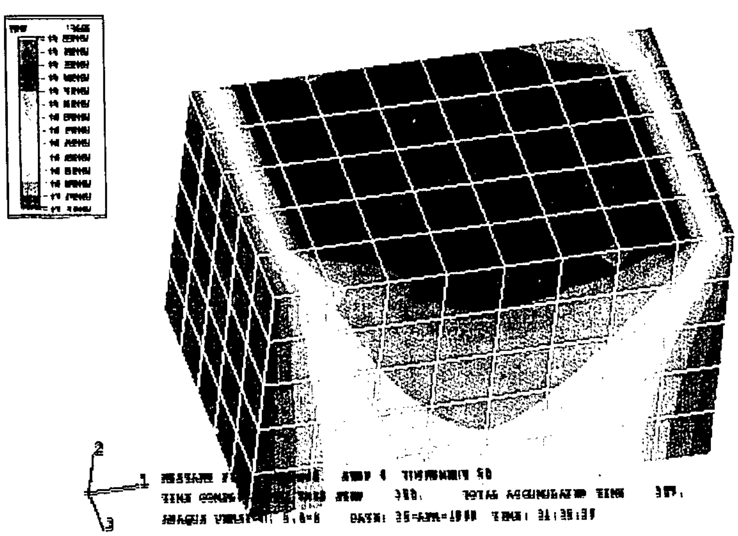


Figure 5-17: *3D Analysis After 257.0 Days*
(Scale: maximum 73.4°F, minimum 50.2°F, interval 1.78°F)



In Figure 5-16, cooling contours due to the cooling coil are extending well into the lift after this time has passed. The concrete has cooled to the point that the ambient temperature is warming the concrete surface at the right and left boundaries, which are approximately at 74°. Near the cooling coils the temperatures are close to 60°.

After 257 days in Figure 5-17, the effect of the cooling coils reaches down to the bottom symmetry boundary. The highest concrete temperatures are at the left and right faces with the ambient temperature applied, at about 73°. Close to the cooling coil, the concrete temperature is about 55°.

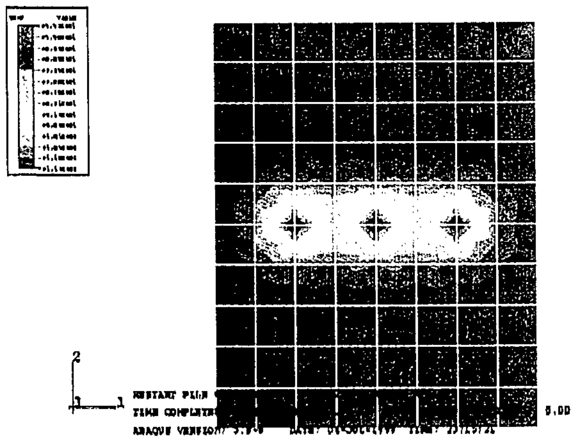
5.1.3 Comparison of 2D and 3D Model Results

It was desirable to compare two-dimensional and three-dimensional results for a similar model to ensure the validity of the analysis in ABAQUS. This process is described below.

2D Model Set-up

The 2-dimensional mesh is designed as shown in Figure 2-5. It includes two 10'V x 16'H lifts. The lifts are both in place at the start of the analysis; they are not placed sequentially. The boundaries were all insulated, no ambient temperatures were applied. This was done so that the 2D and 3D modeling of the cooling coils alone could be observed and compared. Three coils placed at four-foot intervals in the center of the mesh were modeled. Heat generation was included and the placement temperature and the input water temperature were 50° and 75° respectively. The two-dimensional analysis after five days is shown in Figure 5-18. After five days, the maximum concrete temperature is 114°. The cooling coil temperature is 55.3° and the contours created by the cooling coils are apparent.

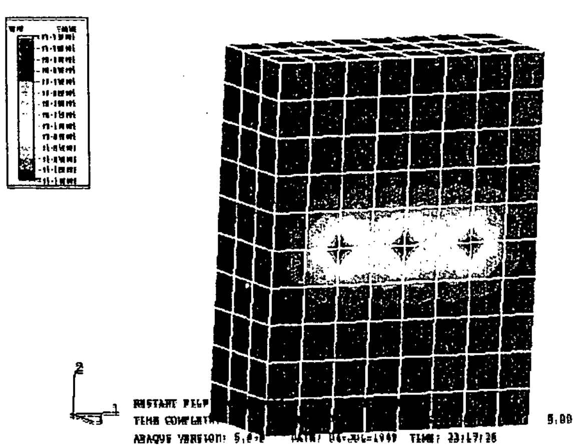
Figure 5-18: *Two Dimensional Analysis After Five Days (for comparison)*
(Scale: maximum 114°F, minimum 55.3°F, interval 4.5°F)



3D Model Set-up

The 3D model is exactly the same as the 2D model except that there is a depth dimension of 10'. The model includes heat generation and insulated boundaries, with placement concrete and cooling input water temperatures of 75° and 50° respectively. After five days, the temperature contour is shown in Figure 5-19. A slice was taken through the model in order to view the temperature contours within the concrete lift section.

Figure 5-19: *Three Dimensional Analysis After Five Days (for comparison)*
(Scale: maximum 114°F, minimum 55.3°F, interval 4.5°F)



The maximum temperature in the concrete is 114°, exactly the same as the 2D model. The cooling water temperature is 55.3°, also consistent with the 2D model.

Results

The following sequence demonstrates the compatibility of the 2D and 3D models.

Figure 5-20: *2D and 3D Analysis After 20.0 Days*
(Scale: maximum 123°F, minimum 53.8°F, interval 5.3°F)

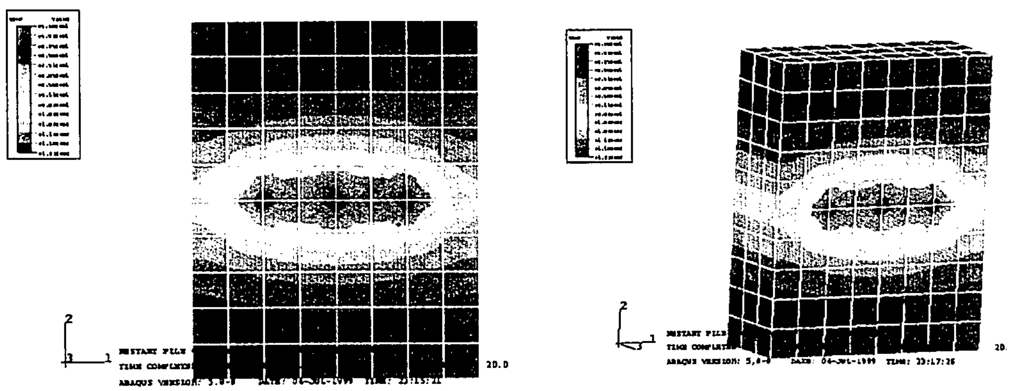
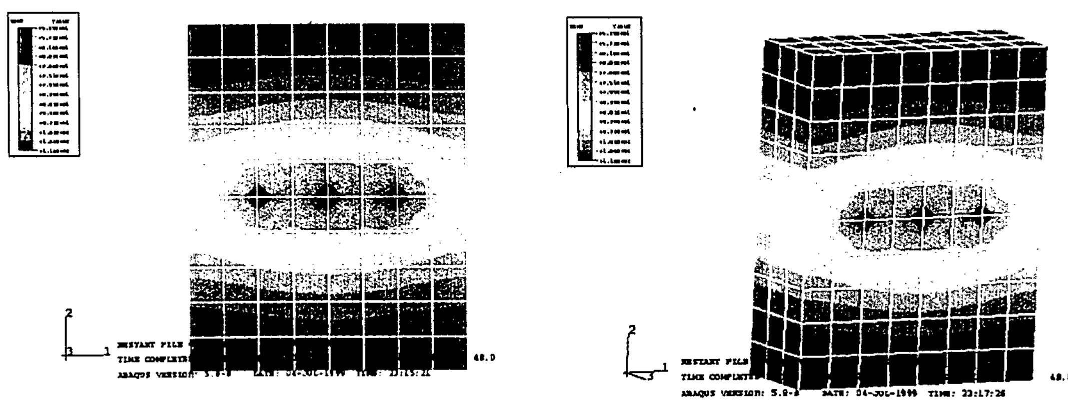


Figure 5-21: *2D and 3D Analysis After 48.0 Days*
(Scale: maximum 110°F, minimum 52.9°F, interval 4.4°F)

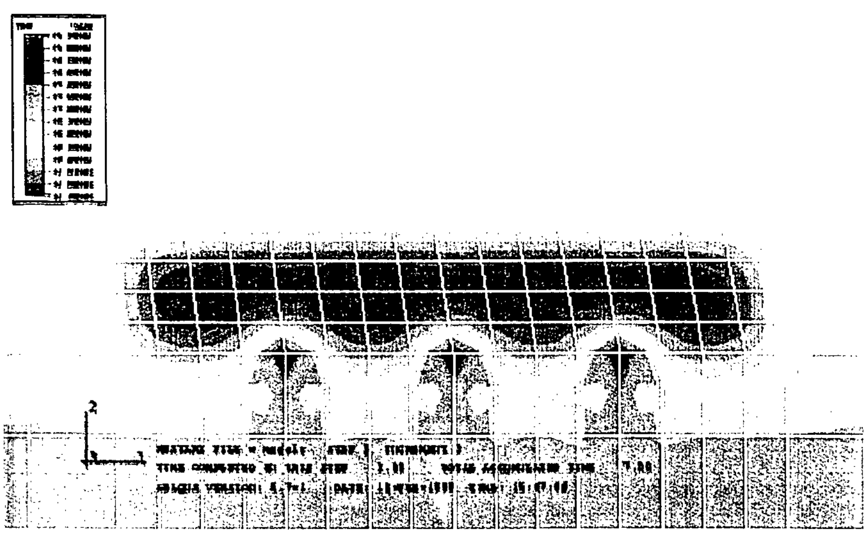


Figures 5-20 and 5-21 both show identical temperature distributions for the two-dimensional and three-dimensional models, verifying the validity of their compatibility.

5.2 Two-Dimensional Portuguese Dam Results

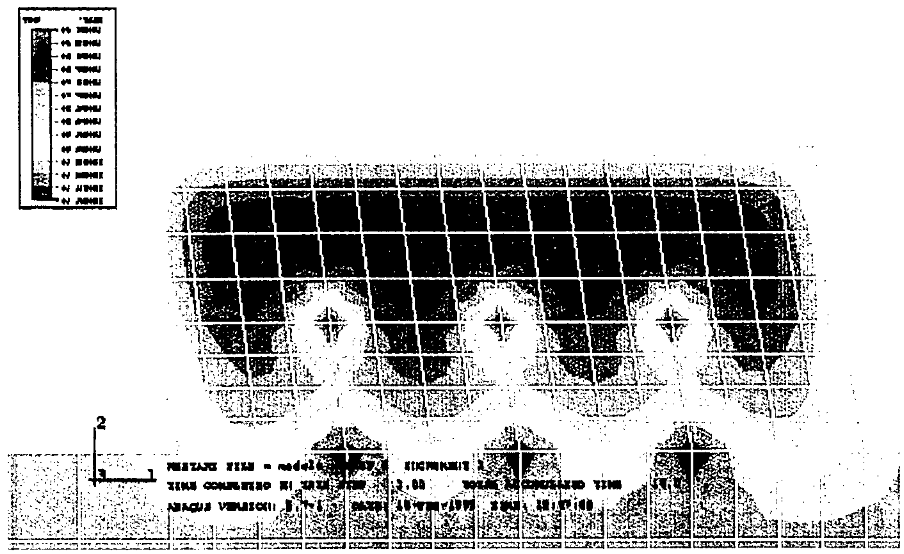
The cooling coil modeling procedure was implemented in existing two-dimensional models of the Portuguese Dam provided by the Army Corp of Engineers. The foundation and first four lifts were analyzed. The model has 2.5' horizontal elements in the lifts with varying vertical element height. Three cooling coils were placed at ten foot increments at the lift-lift or lift-foundation boundaries. The lifts vary in size with horizontal dimensions of 40' and varying vertical dimensions. The ambient temperature was applied to all exposed faces of the lifts. Heat generation was included and the input water temperature was 50°. Figure 5-22 shows the analysis after 7 days.

Figure 5-22: *Portuguese Dam At 7.0 Days*
(Scale: maximum 103°F, minimum 55°F, interval 3.7°F)



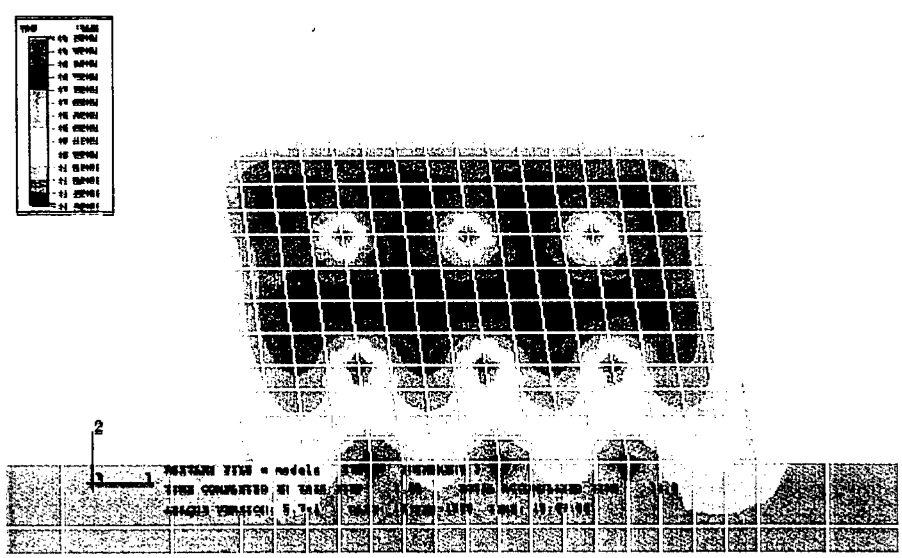
From the start of the analysis the cooling coils between lift 1 and the foundation are activated. After 7 days, the maximum temperature in lift 1 is 110°. The cooling water is at 53.7°. Contours due to cooling by the coils and the ambient temperature are visible. At 7 days, lift two is placed. The temperature after 14 days is shown in Figure 5-23.

Figure 5-23: *Portuguese Dam At 14.0 Days*
(Scale: maximum 115°F, minimum 53.3°F, interval 4.75°F)



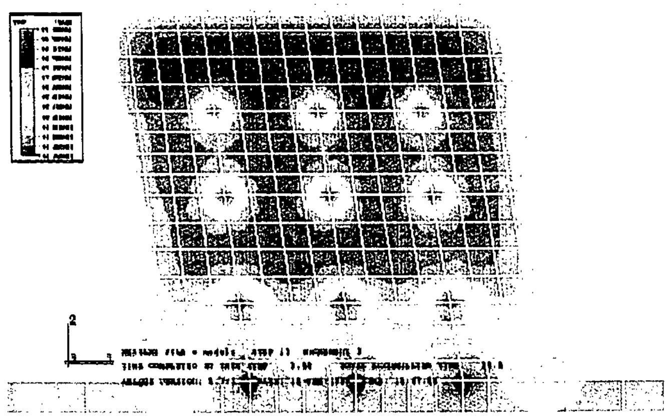
After 14 days, the maximum temperature is experienced in lift 2 at 115°. Both sets of cooling coils are working to cool lift one, whose temperature varies from approximately 93° at the foundation to 108° closer to lift 2. The ambient temperature is cooling the exposed boundaries. At 14 days, lift 3 is placed. At 21 days, the temperature distribution is as shown in Figure 5-24.

Figure 5-24: *Portuguese Dam Analysis At 21.0 Days*
(Scale: maximum 115°F, minimum 53°F, interval 4.75°F)



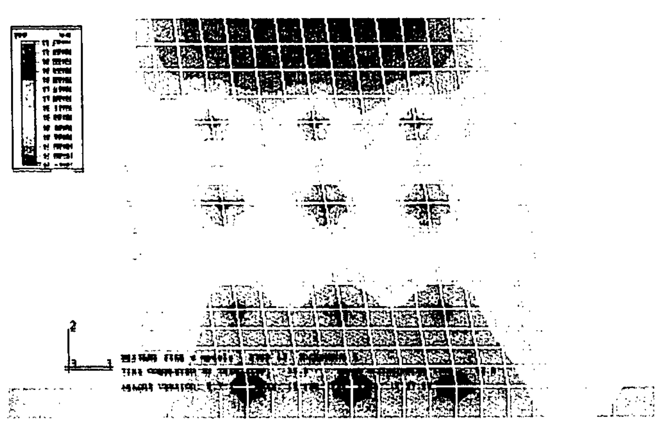
At 21 days, the temperatures of both lift two and three are elevated, at about 115°. The ambient temperature is cooling the boundaries, and the cooling coils are also making an impact. Lift 4 is placed at 21 days, and after 28 days, the temperature contours are as shown in Figure 5-25.

Figure 5-25: *Portuguese Dam Analysis After 28.0 Days*
(Scale: maximum 115°F, minimum 52.8°F, interval 4.78°F)



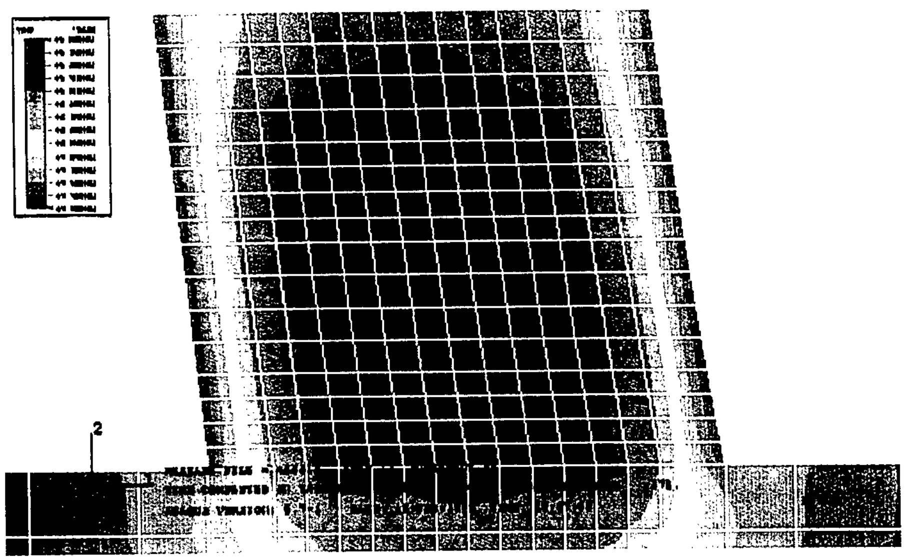
At 28 days, the highest temperatures are experienced in lift 4, at 115°. Lifts 2 and 3 are similar in temperature; about 108°. Lift 1 is significantly cooler due to the cooling coils, and the effects of the ambient temperature cooling are observed along the boundaries. As cooling continues, the temperature continues to diminish, as seen in Figure 5-26 at 53 days.

Figure 5-26: *Portuguese Dam Analysis at 53.0 Days*
(Scale: maximum 111°F, minimum 51.7°F, interval 4.56°F)



After 53 days, the extent of cooling is more extensive. Lift 1 is at approximately 77°, lifts 2 and 3 are about 90°, and the maximum temperature is experienced at the top of lift 4 at 111°. At 278 days, the cooling has advanced substantially, as seen in Figure 5-27.

Figure 5-27: *Portuguese Dam Analysis at 278.0 Days*
(Scale: maximum 79.8°F, minimum 50.3°F, interval 2.25°F)



Cooling at this stage is quite extensive. The lifts have equilibrated in temperature, and the central portion near the coils is about 55°. The ambient temperature at the external boundaries is acting to warm the concrete surfaces at this point.

5.3 Summary

The modeling of embedded cooling coils using boundary temperature nodes can be completed accurately and efficiently with good results as presented in this chapter. The modeling procedure can be modified to work for any massive concrete problem and is relatively easy to implement, which will be discussed in Chapter 6. The cooling coil nodes effectively cool the massive concrete system and errors due to the use of incremental analysis and average concrete node choice are insignificant as presented in Chapter 5.

Chapter 6

Documentation for Cooling Coil Modeling Using ABAQUS Version 5.7 or 5.8

This chapter will cover the use and implementation of the commands and subroutines required to model cooling coils in massive concrete systems using ABAQUS. This chapter will discuss the additions that need to be made to an ABAQUS input file, the additional subroutines required, and how the subroutines perform the necessary tasks.

6.1 Basic Procedure

The procedure developed allows the user to implement a model in ABAQUS that analyzes how a cooling coil draws heat out of a massive concrete system. It allows a user to change the spacing and number of the coils in the system or a particular lift and to turn the coils on or off during different parts of the analysis. It also accounts for changes in the cooling system such as the inlet water temperature, placement temperature of the concrete, etc.

The command used to model the cooling coils is the *BOUNDARY command in ABAQUS. The *BOUNDARY command is applied to nodes only. Therefore the cooling coils need to be located at nodes in the mesh. When designing the mesh, it is important to consider the spacings that will be attempted for cooling coil locations. For example, if the user would like to try 4’, 6’, 8’, and

10' horizontal spacing of cooling coils, they may want to use a 2' node spacing which allow for placement of cooling coils at multiples of 2' increments.

The modeling of the cooling coils employs Y-curves first created during the Boulder Canyon Dam Project as discussed in Chapter 1. The Y-curves allow the ABAQUS subroutines to calculate the exit temperature of the cooling coil water based on the two dimensionless parameters given in Eq. 6-1 and Eq. 6-2:

$$\frac{KL}{c_w \rho_w Q_w} \qquad (6\text{-}1)$$

$$\frac{h_f^{\,2} t}{D^2} \qquad (6\text{-}2)$$

Where:

- K = Conductivity of the concrete to be cooled in B.t.u./ft/hr/°F
- L = Length of the cooled cylinder measured along the cooling pipe in feet
- c_w = specific heat of the cooling water in B.t.u./lb/°F
- ρ_w = density of the cooling water in lb/ft^3
- Q_w = volume of water flowing through the cooling pipe in ft^3/hr
- D = diameter of the cooled cylinder in feet
- h_f^2 = diffusivity of the concrete in ft^2/hr
- t = total elapsed time the cooling coil has been in operation in hours

The Y-curves were computed for a ratio of *b/a* of 100 where *b* is the radius of the cooled cylinder and *a* is the radius of the cooling pipe as discussed in Chapter 1. Actual cooling pipe spacings will rarely result in a *b/a* ratio of 100. In order to take the difference into account, charts have been tabulated that modify the values of *h* and *D* to account for this difference. These modified values were shown for common lift dimensions in Table 2-1.

The Y-curves are shown in Figure 2-1. Eq. 6-1 is plotted along the x-axis, and Eq. 6-2 allows the user to locate one of a series of curves plotted on the Y-chart. Using the intersection point of the x-value with the appropriate curve from the series, the Y-value can be obtained. The Y-value is related to the temperatures of the concrete and water as shown in Eq 4-3.

The ABAQUS analysis is broken down into time increments within steps. The model works by calculating the concrete temperature at the end of an increment. Using the Y-value and the inlet water temperature, the program calculates the exit water temperature for the increment. The exit and inlet water temperatures are averaged to give a mean cooling coil temperature for the increment. Than this average temperature is applied to the node where the cooling coil is located.

The average temperature is applied to the node at the desired location of the cooling coil using the *BOUNDARY command. This command allows the user to place a constraint on a degree of freedom in ABAQUS. In the case of a cooling coil, a temperature boundary condition is placed on the nodes at the locations of the cooling coils. This boundary temperature is controlled by a user subroutine called DISP which is called at the beginning of each increment and recalculates the boundary temperature for each node where the condition is applied. In this way the temperature of the cooling coil can be controlled and kept constant in the model. The nodes with the temperature boundary condition draw heat from the system and cooling it as a cooling coil does in massive concrete systems.

6.2 Implementing the Procedure into an Abaqus Model

Using the procedure requires the user to modify three things in the ABAQUS model. These are the creation of node sets, implementing the *BOUNDARY command, and entering data into the user subroutines. The implementation is exactly the same for both 2D and 3D models except for the cooling node choices.

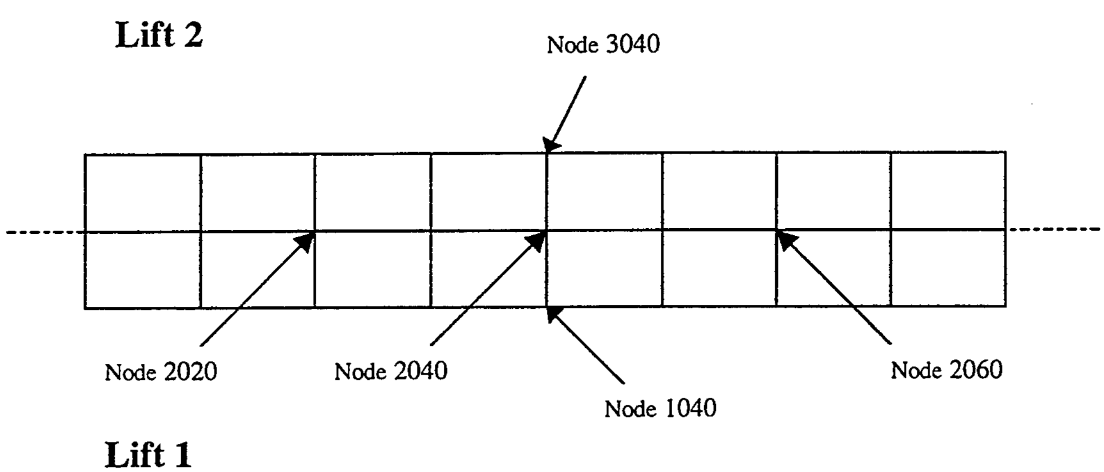
6.2.1 Node Sets Required

Implementation of this procedure requires the creation of several node sets. All node sets must have the names specified here because the subroutines reference the node sets by these designations. The first node sets required are those which include the node numbers of the location of all the cooling coils. These node sets have the designation CC01, CC02, ... CC12 ... CCN where N is the total number of lifts. The numbers 01, 02, etc. represent the cooling coils at the bottom of the lift with the same number. Therefore CC01 are the cooling coils between Lift 1 and the foundation and CC13 are the cooling coils between Lift 12 and Lift 13. Because the cooling coils are included in a node set the user can modify the number and location of the cooling coils by changing the numbers or amount of the nodes included in one of the CC sets to act as the cooling coils for that lift.

The second node sets required are necessary to calculate the concrete temperature at the end of each increment. These node sets have the designation AVG01, AVG02, ... AVG12 ... AVGN where N is the total number of lifts. The numbering works the same as the numbering for the CC node sets. Each 'AVG' node set should include two nodes. These two nodes will give a representation of the concrete temperature. To locate these two nodes, the user should find the radius of the cylinder cooled by their particular spacing for coils found in Table 1. Then 33.3% of the radius should be taken as the distance above and below the cooling coil to find the average concrete temperature. The closest corner node to this distance should be used. Only two nodes, one above and one below the cooling coils, will be used to calculate the average for all the nodes on that lift. This is a valid assumption because the temperature remains relatively constant horizontally along the lift. In addition, it is important that the same average temperature be found for all the cooling nodes in one lift because the exit temperature of the water is dependent on this value and since they are part of the same coil they must all have the same exit temperature. For the 3D models, the average nodes should be above and below the plane of the cooling coil.

For example, if the user's mesh between Lift 01 and Lift 02 was as shown in Figure 6-1:

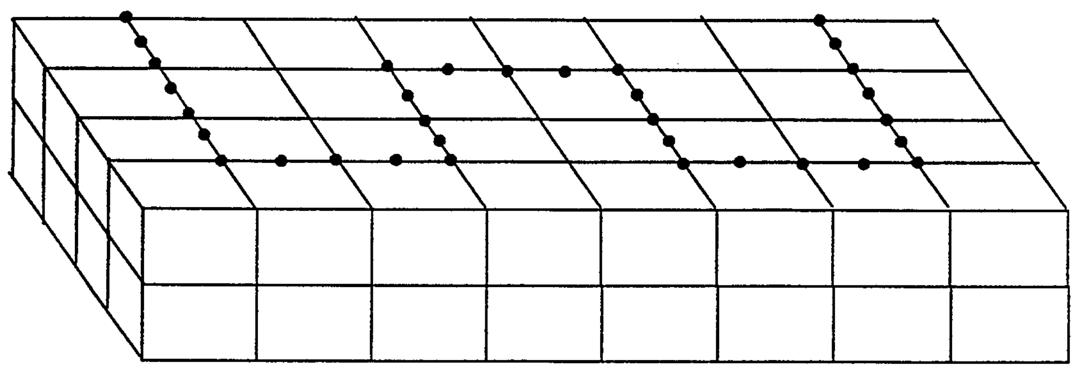
Figure 6-1: *2D Example Mesh*



In this case node set 'CC02' would include 2020, 2040, and 2060 because the cooling coils are located at these points for the analysis. Node set 'AVG02' would include 1040 and 3040.

Three dimensional models are handled in much the same way as shown in Figure 6-2.

Figure 6-2: *3D Example Mesh*



This mesh shows the location of the cooling coil on the top face of a lift with the lift above not shown. If the user wanted the cooling coil to wind in the location shown, every bold node would need to be included in the node set 'CC' corresponding to the lift number of the lift above. Any cooling coil pattern can be used as long as every node along the path is included in the node set 'CC.' The user also needs to specify two average nodes for node set 'AVG.' One node should be chosen above and below the plane of the coils, at or near the halfway point of the coil length. The average nodes chosen should be corner nodes.

Lastly, the user need to create a node set called 'ALL' which includes all the 'AVG' and 'CC' node sets.

The user should keep all these node sets together in a section of the ABAQUS program called 'Cooling Coils.' The section should come directly before the steps, and the format is shown below.

```
************************************************ COOLING COILS
**
**************LIFT1-FOUNDATION
** COOLING COIL NODES
*NSET, NSET=CC01
29, 33, 37
** AVERAGE CONCRETE TEMP. NODES
*NSET, NSET=AVG01
129, 5020
**
**************LIFT2-LIFT1
** COOLING COIL NODES
*NSET, NSET=CC02
11, 15, 19
** AVERAGE CONCRETE TEMP. NODES
*NSET, NSET=AVG02
136, 338
**
**************LIFT3-LIFT2
**  COOLING COIL NODES
*NSET, NSET=CC03
242, 246, 250
** AVERAGE CONCRETE TEMP. NODES
*NSET, NSET=AVG03
344, 538
**
***************
*NSET, NSET=ALL
CC01, CC02, CC03, AVG01, AVG02, AVG03
**
```

6.2.2 *BOUNDARY and *NODE FILE Commands

The *BOUNDARY command needs to be included in *every* step in the analysis. The node sets for all the cooling coils activated in the step need to be included as shown below.

```
*BOUNDARY, OP=NEW, USER
CC01, 11, 11
CC02, 11, 11
CC03, 11, 11
```

The USER command indicates that the boundary temperature applied is controlled by a user subroutine (DISP). The node sets are given, followed by the starting and ending degrees of freedom which are both 11 (degree of freedom for temperature).

If the user would like to activate cooling coils only during specific steps in the analysis, this is easily accomplished by including the *BOUNDARY command but not including specific sets within the command. The command still needs to be included because the OP=NEW parameter erases all the applied boundaries already in place. This is shown below.

```
*BOUNDARY, OP=NEW, USER
```

In addition, *NODE FILE must be included in *every step*. The node set 'All' should be indicated on the command line. For the variable to be written to the results file the user should type 'NT' as shown below.

```
*NODE FILE, NSET=ALL
NT
```

It is important to remember not to activate the coils for a particular lift until the lift has been put in place! In the following example, Lift 1 is placed in Step 1 and the cooling coils between Lift 1 and the Foundation are activated in this step (CC01). Lift 2 is not added until Step 4 at which time the cooling coils between Lift 1 and Lift 2 are activated.

```
** STEP 1, place lift no. 1
**
*STEP
*HEAT TRANSFER
.25,2
*MODEL CHANGE, REMOVE
START
*FILM, AMPLITUDE=SUMMER, OP=NEW
USELS,F4,,90.288
DSELS,F2,,90.288
TLT01,F3,,90.288
*BOUNDARY, OP=NEW, USER  <------------------------
CC01, 11, 11
*NODE FILE,NSET=ALL
NT
*RESTART,WRITE,FREQUENCY=2
*ENDSTEP
**
** STEP 2
**
*STEP
*HEAT TRANSFER
.5,3
*FILM, AMPLITUDE=SUMMER, OP=NEW
USELS,F4,,90.288
DSELS,F2,,90.288
TLT01,F3,,90.288
*BOUNDARY, OP=NEW, USER  <------------------------
CC01, 11, 11
*NODE FILE,NSET=ALL
```

```
NT
*RESTART,WRITE,FREQUENCY=2
*ENDSTEP
**
** STEP 3
**
*STEP
*HEAT TRANSFER
1.0,2
*FILM, AMPLITUDE=SUMMER, OP=NEW
USELS,F4,,90.288
DSELS,F2,,90.288
TLT01,F3,,90.288
*BOUNDARY, OP=NEW, USER
CC01, 11, 11
*NODE FILE,NSET=ALL
NT
*RESTART,WRITE,FREQUENCY=2
*ENDSTEP
**
** STEP 4, place lift no. 2
**
*STEP
*HEAT TRANSFER
.25,2
*MODEL CHANGE, ADD
LFT02
*FILM, AMPLITUDE=SUMMER, OP=NEW
USELS,F4,,90.288
DSELS,F2,,90.288
TLT02,F3,,90.288
*BOUNDARY, OP=NEW, USER
CC01, 11, 11
CC02, 11, 11
*NODE FILE,NSET=ALL
NT
*RESTART,WRITE,FREQUENCY=2
*ENDSTEP
**
ETC.
```

6.2.3 Subroutine Modification

The user is required to enter certain information into both the DISP and URDFIL subroutines which must be included at the end of the ABAQUS input file. In the DISP routine, the user must enter the input water temperature (1), the concrete placement temperature (2), and the Y-value for the first increment (3). In addition, Y-values for every increment time and length of coil in the analysis must be entered (4). As shown below, the subroutine has Y-values defined for 0.25, 0.5, 1.0, 5.0, 7.0, 14.0, and 15.0 day increments and coil lengths of 480 and 600 feet. The user should calculate these Y-values using the Y-curves as described in section 6.1. In Eq. 6-1, the parameters K, c_w, ρ_w, and Q_w are known and should not change during the analysis. The length of the coil may change however as the lifts change in size. Therefore, different lifts may have different lengths of coil. The different coil lengths are associated with their respective lift numbers in the loop at location (6). In Eq. 6-2, the h, D, and t (incremental time) values will change with different cooling coil spacing and incremental times within the analysis. The user should calculate different values for Y based on these different increment times. If a different increment time or length other than those listed above is used, the user must add it at location (5) and accommodate it in the loop at location (6). The loop at location (6) chooses the correct Y-value based on the increment time and the lift number. The lift number accounts for the different lengths of coil for different lifts if necessary. Lastly, the user must change the dimensions of the arrays KCC and KAVG if necessary, as explained in number (7). The DISP routine is shown below:

```
      SUBROUTINE DISP(U, KSTEP, KINC, TIME, NODE, JDOF)
      INCLUDE 'ABA_PARAM.INC'
      COMMON KCC,KAVG,KTIME
      REAL*8 KAVG,KTIME
      DIMENSION U(3), TIME(2)
C
C     KCC AND KAVG ARE DIMENSIONED AS KCC(NUMBER OF COIL NODES, NUMBER OF
C     LIFTS) AND KAVG(2, NUMBER OF LIFTS). IF THE MODEL REQUIRES MORE
C     LIFTS OR COILS THAN LISTED CURRENTLY SHOWN, THE USER MUST CHANGE THE
C     DIMENSION!!! AFTER CHANGING THE DIMENSIONS FOR KCC AND KAVG, THE
C     USER MUST ALSO CHANGE THE 'NCOIL' VALUE TO THE MAXIMUM NUMBER OF
C     COIL NODES PER LIFT AND THE 'NLIFT' VALUE TO THE MAXIMUM NUMBER OF      7
C     LIFTS. THE DIMENSIONS FOR THE ARRAYS SHOULD CORRESPOND TO THE NCOIL
C     AND NLIFT DEFINITIONS.
C
DIMENSION KCC(20,50), KAVG(2,50)
NCOIL=20
NLIFT=50
C
C     DEFINE VARIABLES
C
C     ENTER THE INITIAL COOLING WATER TEMPERATURE IN DEG. F
      WTEMP=50.00                                                           1
C
C     ENTER THE PLACEMENT TEMPERATURE OF CONCRETE                           2
      PT=75.00
C
C     ENTER THE Y-VALUE FOR THE FIRST INCREMENT                             3
      YFI=0.22772
C
```

```
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 0.25 DAYS AND 280 FEET
    Y25L280=0.22772
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 0.50 DAYS AND 280 FEET
    Y50L280=0.19146
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 1.0 DAYS AND 280 FEET          4
    Y1L280=0.163
C
C   ENTER THE Y=VALUE CORRESPONDING TO A TIME OF 5.0 DAYS AND 280 FEET
    Y5L280=0.13
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 7.0 DAYS AND 280 FEET
    Y7L280=0.12
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 14.0 DAYS AND 480 FEET
    Y14L280=0.11
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 15.0 DAYS AND 480 FEET
    Y15L280=0.11
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 0.25 DAYS AND 600 FEET
    Y25L600=0.24
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 0.50 DAYS AND 600 FEET
    Y50L600=0.217
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 1.0 DAYS AND 600 FEET
    Y1L600=0.18
C
C   ENTER THE Y=VALUE CORRESPONDING TO A TIME OF 5.0 DAYS AND 600 FEET
    Y5L600=0.15
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 7.0 DAYS AND 600 FEET
    Y7L600=0.143
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 14.0 DAYS AND 600 FEET
    Y14L600=0.12
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 15.0 DAYS AND 600 FEET
    Y15L600=0.12
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF ____ DAYS AND ____ FEET
    Y___=____                                                                  5
C                                                        Added if necessary by user
C
    IF (KSTEP.EQ.1 .AND. KINC.EQ.1) THEN
       TINC=TFI
    ELSE
       TINC=TIME(2)-KTIME
    END IF
C
    DO 50 N=1,NCOIL
       DO 40 M=1,NLIFT
```

```
            IF (NODE.EQ.KCC(N,M)) THEN
              LIFT=M
            END IF
 40 CONTINUE
 50 CONTINUE
C
      IF (TINC.LE.0.25 .AND. LIFT.EQ.1) THEN
        Y=Y25L600
      ELSE IF (TINC.GT.0.25 .AND. TINC.LE.0.5 .AND. LIFT.EQ.1) THEN
        Y=Y50L600
      ELSE IF (TINC.GT.0.5 .AND. TINC.LE.1.0 .AND. LIFT.EQ.1) THEN
        Y=Y1L600
      ELSE IF (TINC.GT.1.0 .AND. TINC.LE.5.0 .AND. LIFT.EQ.1) THEN
        Y=Y5L600
      ELSE IF (TINC.GT.5.0 .AND. TINC.LE.7.0 .AND. LIFT.EQ.1) THEN
        Y=Y7L600
      ELSE IF (TINC.GT.7.0 .AND. TINC.LE.14.0 .AND. LIFT.EQ.1) THEN
        Y=Y14L600
      ELSE IF(TINC.EQ.15.0 .AND. LIFT.EQ.1) THEN
        Y=Y15L600
      ELSE IF(TINC.LE.0.25 .AND. LIFT.EQ.2) THEN
        Y=Y25L280
      ELSE IF (TINC.GT.0.25 .AND. TINC.LE.0.5 .AND. LIFT.EQ.2) THEN
        Y=Y50L280
      ELSE IF (TINC.GT.0.5 .AND. TINC.LE.1.0 .AND. LIFT.EQ.2) THEN
        Y=Y1L280
      ELSE IF (TINC.GT.1.0 .AND. TINC.LE.5.0 .AND. LIFT.EQ.2) THEN
        Y=Y5L280
      ELSE IF (TINC.GT.5.0 .AND. TINC.LE.7.0 .AND. LIFT.EQ.2) THEN
        Y=Y7L280
      ELSE IF (TINC.GT.7.0 .AND. TINC.LE.14.0 .AND. LIFT.EQ.2) THEN
        Y=Y14L280
      ELSE IF (TINC.EQ.15.0 .AND. LIFT.EQ.2) THEN
        Y=Y15L280
      ELSE
        Y=Y15
      END IF
C
      CONCT=(KAVG(1,LIFT)+KAVG(2,LIFT))/2
C
      IF (KINC.EQ.1 .AND. KSTEP.EQ.1) THEN
        U(1)=((YFI*(PT-WTEMP)+WTEMP)+WTEMP)/2
      ELSE
        U(1)=((Y*(CONCT-WTEMP)+WTEMP)+WTEMP)/2
      END IF
C
      RETURN
      END
```

This loop is modified as necessary by the user. Create a position for the time increment, lift number, and the Y-value for that increment time and length of coil for that particular lift.

6

There is only one parameter in addition to the array dimensions discussed above that needs to be modified in the subroutine URDFIL. This is the file name. The file name that needs to be entered is the name of the input file for the particular model being run. It is entered, without the ending, in single quotation marks. For the example shown below, the file name was modelr.inp (8). Lastly, the user must change the dimensions of the arrays KCC and KAVG if necessary, as explained in number (7) above for the DISP routine. Only the beginning of the URDFIL subroutine is shown below because this is the only portion of the routine which requires modification by the user.

```
      SUBROUTINE URDFIL(LSTOP,LOVRWRT,KSTEP,KINC)
      INCLUDE 'ABA_PARAM.INC'
C
C     KCC AND KAVG ARE DIMENSIONED AS KCC(NUMBER OF COIL NODES, NUMBER OF
C     LIFTS) AND KAVG(2, NUMBER OF LIFTS). IF THE MODEL REQUIRES MORE
C     LIFTS OR COILS THAN LISTED CURRENTLY SHOWN, THE USER MUST CHANGE THE
C     DIMENSION!!! AFTER CHANGING THE DIMENSIONS FOR KCC AND KAVG, THE
C     USER MUST ALSO CHANGE THE 'NCOIL' VALUE TO THE MAXIMUM NUMBER OF      7
C     COIL NODES PER LIFT AND THE 'NLIFT' VALUE TO THE MAXIMUM NUMBER OF
C     LIFTS. THE DIMENSIONS FOR THE ARRAYS SHOULD CORRESPOND TO THE NCOIL
C     AND NLIFT DEFINITIONS.
C
DIMENSION KCC(20,50),IAVG(2,50), KAVG(2,50)
      DIMENSION ARRAY(513),JRRAY(NPRECD,513)
      EQUIVALENCE (ARRAY(1),JRRAY(1,1))
      COMMON KCC,KAVG,KTIME
      CHARACTER*80 FNAME
      REAL*8 KAVG,KTIME
NCOIL=20
NLIFT=50
ICOUNT1=0
      ICOUNT2=0
      IVAR=0
C
C     ENTER THE NAME OF THE INPUT FILE IN SINGLE QUOTES IWTHOUT THE
C     EXTENTION
      FNAME='modelr'                                                    8
C
      DO 100 K1=1,99999
C
      DO 10 I=1,513
         ARRAY(I)=0.0
 10   CONTINUE
C
```

For the user who wants a more in depth explanation of the subroutines, their explanation is included in the appendix.

Chapter 7

Conclusions

This chapter will summarize the advantages and disadvantages of the boundary temperature modeling procedure. It will also discuss possible future work.

7.1 Model Advantages and Disadvantages

The boundary node method for modeling the cooling coils has several advantages, and also disadvantages as outlined below.

7.1.1 Advantages

A major advantage of using the boundary method of modeling the cooling coils is that it is easily implemented into an existing model. No change of the mesh is required, and no special mesh, element size, or node placement is required to use the procedure. The actual mechanics of implementing the procedure into a model are outlined in Chapter 6. However, the implementation is not rigorous, and requires no subroutine modification by the user beyond entering certain parameters such as Y-values, placement concrete temperature, and input water temperature. Also, implementation is essentially the same in the two-dimensional and three-dimensional analysis, reducing confusion for the user.

The two-dimensional model would be most likely used to try a variety of cooling coil spacings and designs. It is easy to modify the cooling coil spacings as long as the user has nodes placed where they would like to place coils. In addition, the three dimensional model can accommodate any winding pattern for the cooling coils layout.

Another important point to emphasize is that the model does not require that the cooling coils be functional for the duration of the analysis. The coils can be turned on for any steps in the analysis, then turned off when the user would like to stop cooling. They can also be turned back on later in the analysis if desired by the user.

7.1.2 Disadvantages

The most important disadvantage to the boundary node method of modeling the cooling coils is the reliance on the Y-curves. The Y-curves were developed based on several assumptions, including an insulated cylinder, a straight coil, and non-incremental analysis. However, the curves have been used extensively by the Army Corp of Engineers since the construction of the Hoover Dam, with good results. In addition, as has been established, the error due to an incremental analysis is minor. However, a method of analysis which does not require the use of the Y-curves would be desirable.

The other disadvantage of using boundary nodes to model the coils is that the coils must be placed at node locations. Due to this constraint, the user should consider possible spacing options before creating their mesh in order to choose a node spacing which allows for analysis of several coil spacing options.

7.2 Future Work

The development of a modeling procedure that could be used to verify the Y-curves is still sought-after. It does not necessarily have to be implemented for design, only to verify the curves. The convection/diffusion modeling methods available to model forced convection through a mesh in ABAQUS, while proven not to be adequate for design, may still have the potential to be used as a verification of the Y-curves.

Appendix A

Subroutine URDFIL

```
      SUBROUTINE URDFIL(LSTOP,LOVRWRT,KSTEP,KINC)
      INCLUDE 'ABA_PARAM.INC'
C
C  KCC AND KAVG ARE DIMENSIONED AS KCC(NUMBER OF COIL NODES, NUMBER OF
C  LIFTS) AND KAVG(2, NUMBER OF LIFTS).  IF THE MODEL REQUIRES MORE
C  LIFTS OR COILS THAN LISTED CURRENTLY SHOWN, THE USER MUST CHANGE THE
C  DIMENSION!!!  AFTER CHANGING THE DIMENSIONS FOR KCC AND KAVG, THE
C  USER MUST ALSO CHANGE THE 'NCOIL' VALUE TO THE MAXIMUM NUMBER OF
C  COIL NODES PER LIFT AND THE 'NLIFT' VALUE TO THE MAXIMUM NUMBER OF
C  LIFTS.  THE
C  DIMENSIONS FOR THE ARRAYS SHOULD CORRESPOND TO THE NCOIL AND NLIFT
C  DEFINITIONS.
C
      DIMENSION KCC(20,50),IAVG(2,50), KAVG(2,50)
```

KCC is the array which stores the node numbers of the cooling coil nodes. It assumes no more than 20 cooling coils per lift and 50 lifts unless modified as stated above. IAVG is an array which stores the node numbers of the average concrete temperature nodes. There are only two average nodes per lift and it again assumes 50 lifts unless modified. KAVG is an array which stores the temperature of the nodes in IAVG. NCOIL and NLIFT correspond to the maximum number of coils and lifts as defined in the dimension statements for KCC, KAVG, and IAVG.

```
      DIMENSION ARRAY(513),JRRAY(NPRECD,513)
      EQUIVALENCE (ARRAY(1),JRRAY(1,1))
      COMMON KCC,KAVG,KTIME
```

These three variables need to be passed to the subroutine DISP and are called out as common blocks.

```
      CHARACTER*80 FNAME
      REAL*8 KAVG,KTIME
      NCOIL=20
      NLIFT=50
      ICOUNT1=0
      ICOUNT2=0
```

```
      IVAR=0
C
C     ENTER THE NAME OF THE INPUT FILE IN SINGLE QUOTES WITHOUT THE
C     EXTENTION
      FNAME='modelr'
```

File name of the *.fil (results file) which Abaqus reads to get the node temperature during the analysis.

```
C
      DO 100 K1=1,99999
C
      DO 10 I=1,513
         ARRAY(I)=0.0
 10   CONTINUE
```

This loop initializes the values of Array to 0.

```
C
      CALL DBFILE(0,ARRAY,JRCD)
      IF(JRCD.NE.0)GO TO 110
      KEY=JRRAY(1,2)
```

Every time this call to DBFILE is made Abaqus calls a new record. The following code is completed for that particular record which may or may not have the information needed. Then the next record is called and the process is repeated until all the records have been read. When this happens JRCD is set to something other than zero and the routine ends. KEY is the number designation of every record.

```
C
      IF (KEY.EQ.1931) THEN
```

KEY 1931 contains the information for node sets including the node set name and the numbers of all the nodes included in the set.

```
C
         IF (ARRAY(3).EQ.'CC01') THEN
            ICOUNT1=1
         ELSE IF (ARRAY(3).EQ.'CC02') THEN
            ICOUNT1=2
         ELSE IF (ARRAY(3).EQ.'CC03') THEN
            ICOUNT1=3
         ELSE IF (ARRAY(3).EQ.'CC04') THEN
            ICOUNT1=4
         ELSE IF (ARRAY(3).EQ.'CC05') THEN
            ICOUNT1=5
         ELSE IF (ARRAY(3).EQ.'CC06') THEN
            ICOUNT1=6
         ELSE IF (ARRAY(3).EQ.'CC07') THEN
            ICOUNT1=7
         ELSE IF (ARRAY(3).EQ.'CC08') THEN
            ICOUNT1=8
         ELSE IF (ARRAY(3).EQ.'CC09') THEN
            ICOUNT1=9
         ELSE IF (ARRAY(3).EQ.'CC10') THEN
            ICOUNT1=10
         ELSE IF (ARRAY(3).EQ.'CC11') THEN
            ICOUNT1=11
         ELSE IF (ARRAY(3).EQ.'CC12') THEN
            ICOUNT1=12
         ELSE IF (ARRAY(3).EQ.'CC13') THEN
            ICOUNT1=13
```

```
      ELSE IF (ARRAY(3).EQ.'CC14') THEN
         ICOUNT1=14
      ELSE IF (ARRAY(3).EQ.'CC15') THEN
         ICOUNT1=15
      ELSE IF (ARRAY(3).EQ.'CC16') THEN
         ICOUNT1=16
      ELSE IF (ARRAY(3).EQ.'CC17') THEN
         ICOUNT1=17
      ELSE IF (ARRAY(3).EQ.'CC18') THEN
         ICOUNT1=18
      ELSE IF (ARRAY(3).EQ.'CC19') THEN
         ICOUNT1=19
      ELSE IF (ARRAY(3).EQ.'CC20') THEN
         ICOUNT1=20
      ELSE IF (ARRAY(3).EQ.'CC21') THEN
         ICOUNT1=21
      ELSE IF (ARRAY(3).EQ.'CC22') THEN
         ICOUNT1=22
      ELSE IF (ARRAY(3).EQ.'CC23') THEN
         ICOUNT1=23
      ELSE IF (ARRAY(3).EQ.'CC24') THEN
         ICOUNT1=24
      ELSE IF (ARRAY(3).EQ.'CC25') THEN
         ICOUNT1=25
      ELSE IF (ARRAY(3).EQ.'CC26') THEN
         ICOUNT1=26
      ELSE IF (ARRAY(3).EQ.'CC27') THEN
         ICOUNT1=27
      ELSE IF (ARRAY(3).EQ.'CC28') THEN
         ICOUNT1=28
      ELSE
         ICOUNT1=0
      END IF
```

If the KEY=1931, Array(3) contains the nodeset name. If Array(3) matches the CC* name shown above, the variable ICOUNT1 is set to the lift number.

```
C
      IF (ICOUNT1.GT.0) THEN
         DO 20 N=1,NCOIL
            KCC(N,ICOUNT1)=JRRAY(1,3+N)
20       CONTINUE
      END IF
```

If ICOUNT1 is equal to a lift number (greater than 0) then this loop fills the array KCC with the node numbers included in the node set corresponding to that lift. These numbers are in JRRAY(1,3...End of set).

```
C
C
    IF (ARRAY(3).EQ.'AVG01') THEN
         ICOUNT2=1
      ELSE IF (ARRAY(3).EQ.'AVG02') THEN
         ICOUNT2=2
      ELSE IF (ARRAY(3).EQ.'AVG03') THEN
         ICOUNT2=3
      ELSE IF (ARRAY(3).EQ.'AVG04') THEN
         ICOUNT2=4
```

```
      ELSE IF (ARRAY(3).EQ.'AVG05') THEN
         ICOUNT2=5
      ELSE IF (ARRAY(3).EQ.'AVG06') THEN
         ICOUNT2=6
      ELSE IF (ARRAY(3).EQ.'AVG07') THEN
         ICOUNT2=7
      ELSE IF (ARRAY(3).EQ.'AVG08') THEN
         ICOUNT2=8
      ELSE IF (ARRAY(3).EQ.'AVG09') THEN
         ICOUNT2=9
      ELSE IF (ARRAY(3).EQ.'AVG10') THEN
         ICOUNT2=10
      ELSE IF (ARRAY(3).EQ.'AVG11') THEN
         ICOUNT2=11
      ELSE IF (ARRAY(3).EQ.'AVG12') THEN
         ICOUNT2=12
      ELSE IF (ARRAY(3).EQ.'AVG13') THEN
         ICOUNT2=13
      ELSE IF (ARRAY(3).EQ.'AVG14') THEN
         ICOUNT2=14
      ELSE IF (ARRAY(3).EQ.'AVG15') THEN
         ICOUNT2=15
      ELSE IF (ARRAY(3).EQ.'AVG16') THEN
         ICOUNT2=16
      ELSE IF (ARRAY(3).EQ.'AVG17') THEN
         ICOUNT2=17
      ELSE IF (ARRAY(3).EQ.'AVG18') THEN
         ICOUNT2=18
      ELSE IF (ARRAY(3).EQ.'AVG19') THEN
         ICOUNT2=19
      ELSE IF (ARRAY(3).EQ.'AVG20') THEN
         ICOUNT2=20
      ELSE IF (ARRAY(3).EQ.'AVG21') THEN
         ICOUNT2=21
      ELSE IF (ARRAY(3).EQ.'AVG22') THEN
         ICOUNT2=22
      ELSE IF (ARRAY(3).EQ.'AVG23') THEN
         ICOUNT2=23
      ELSE IF (ARRAY(3).EQ.'AVG24') THEN
         ICOUNT2=24
      ELSE IF (ARRAY(3).EQ.'AVG25') THEN
         ICOUNT2=25
      ELSE IF (ARRAY(3).EQ.'AVG26') THEN
         ICOUNT2=26
      ELSE IF (ARRAY(3).EQ.'AVG27') THEN
         ICOUNT2=27
      ELSE IF (ARRAY(3).EQ.'AVG28') THEN
         ICOUNT2=28
      ELSE
         ICOUNT2=0
      END IF
C
      IF (ICOUNT2.GT.0) THEN
         DO 30 N=1,2
```

```
                IAVG(N,ICOUNT2)=JRRAY(1,3+N)
 30           CONTINUE
          END IF
      END IF
```

This section stores the node numbers included in the KAVG* node sets in the same way as those above for the CC* node sets.

```
C
      IF (KEY.EQ.2000) THEN
```

KEY 2000 stores information including the step number, increment number, and total time.

```
         KISTEP=JRRAY(1,8)
         KSINC=JRRAY(1,9)
```

It is necessary to know the total time when this routine is called at the end of the increment. To find the total time we needed to find the current step and increment in the *.fil file. To do this we needed to compare the current step and increment (read in as KSTEP and KINC in the subroutine call) and compare these with the KISTEP and KSINC values defined above which give the step and increment in the *.fil file. The Abaqus utility routine POSFIL could not be used to position us at the current step and increment in the *.fil file because it positioned us after the keys 1931 and 2000 which we needed.

```
         IF (KINC.EQ.KSINC .AND. KSTEP.EQ.KISTEP) THEN
            IVAR=1
            KTIME=ARRAY(3)
         ELSE
            IVAR=0
         END IF
      END IF
```

KTIME is the total time at the end of the current increment. IVAR is a dummy variable to indicate whether or not we are at the current step and increment in the *.fil file.

```
C
      IF (IVAR.EQ.1 .AND. KEY.EQ.201) THEN
```

If IVAR=1 than we are positioned at the current step and increment in the *.fil file. KEY 201 contains the node number in position JRRAY(1,3) and the node temperature in ARRAY(1,4).

```
         DO 60 N=1,2
            DO 50 M=1,NLIFT
            IF (JRRAY(1,3).EQ.IAVG(N,M)) THEN
               KAVG(N,M)=ARRAY(4)
            END IF
```

This loop fills array KAVG with the node temperatures of the nodes in array IAVG.

```
 50         CONTINUE
 60      CONTINUE
      END IF
C
 100     CONTINUE
 110     CONTINUE
      RETURN
      END
```

Appendix B

Subroutine DISP

```
      SUBROUTINE DISP(U, KSTEP, KINC, TIME, NODE, JDOF)
      INCLUDE 'ABA_PARAM.INC'
      COMMON KCC,KAVG,KTIME
```

These arrays are read in from the URDFIL subroutine. The URDFIL subroutine is called at the end of the increment. DISP is called at the beginning of the increment. Therefore KAVG, and KTIME are the average node temperatures and the total time for the previous increment.

```
      REAL*8 KAVG,KTIME
      DIMENSION U(3), TIME(2)
C
C KCC AND KAVG ARE DIMENSIONED AS KCC(NUMBER OF COIL NODES, NUMBER OF
C LIFTS) AND KAVG(2, NUMBER OF LIFTS). IF THE MODEL REQUIRES MORE
C LIFTS OR COILS THAN LISTED CURRENTLY SHOWN, THE USER MUST CHANGE THE
C DIMENSION!!! AFTER CHANGING THE DIMENSIONS FOR KCC AND KAVG, THE
C USER MUST ALSO CHANGE THE 'NCOIL' VALUE TO THE MAXIMUM NUMBER OF
C COILS PER LIFT AND THE 'NLIFT' VALUE TO THE MAXIMUM NUMBER OF LIFTS.
C THE
C DIMENSIONS FOR THE ARRAYS SHOULD CORRESPOND TO THE NCOIL AND NLIFT
C DEFINITIONS.
C
      DIMENSION KCC(20,50), KAVG(2,50)
      NCOIL=20
      NLIFT=50
```

KCC is the array which stores the node numbers of the cooling coil nodes. It assumes no more than 20 cooling coils per lift and 50 lifts unless modified as stated above. There are only two average nodes per lift and it again assumes 50 lifts unless modified. KAVG is an array which stores the temperature of the nodes in IAVG. NCOIL and NLIFT correspond to the maximum number of coils and lifts as defined in the dimension statements for KCC, KAVG, and IAVG.

```
C
C  DEFINE VARIABLES
C
C  ENTER THE INITIAL COOLING WATER TEMPERATURE IN DEG. F
      WTEMP=50.00
```

```
C
C   ENTER THE PLACEMENT TEMPERATURE OF CONCRETE
    PT=75.00
C
C   ENTER THE Y-VALUE FOR THE FIRST INCREMENT
    YFI=0.25
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 0.25 DAYS AND 480
C   FEET
    Y25L480=0.24
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 0.50 DAYS AND 480
C   FEET
    Y50L480=0.217
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 1.0 DAYS AND 480
C   FEET
    Y1L480=0.18
C
C   ENTER THE Y=VALUE CORRESPONDING TO A TIME OF 5.0 DAYS AND 480
C   FEET
    Y5L480=0.15
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 7.0 DAYS AND 480
C   FEET
    Y7L480=0.143
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 14.0 DAYS AND 480
C   FEET
    Y14L480=0.12
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 15.0 DAYS AND 480
C   FEET
    Y15L480=0.12
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 0.25 DAYS AND 600
C   FEET
    Y25L600=0.24
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 0.50 DAYS AND 600
C   FEET
    Y50L600=0.217
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 1.0 DAYS AND 600
C   FEET
    Y1L600=0.18
C
C   ENTER THE Y=VALUE CORRESPONDING TO A TIME OF 5.0 DAYS AND 600
C   FEET
    Y5L600=0.15
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 7.0 DAYS AND 600
C   FEET
    Y7L600=0.143
```

```
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 14.0 DAYS AND 600
C   FEET
    Y14L600=0.12
C
C   ENTER THE Y-VALUE CORRESPONDING TO A TIME OF 15.0 DAYS AND 600
C   FEET
    Y15L600=0.12
C
```

User defined variables.

```
C
    IF (KSTEP.EQ.1 .AND. KINC.EQ.1) THEN
       TINC=TFI
    ELSE
       TINC=TIME(2)-KTIME
    END IF
```

If the current step and increment are both one (KSTEP and KINC=1), it is the first increment of the analysis. If it is a later step, TIME(2) is the total time at the end of the current increment. By subtracting the total time from the previous increment (KTIME), the increment time (TINC) is determined.

```
C
    DO 50 N=1,NCOIL
       DO 40 M=1,NLIFT
          IF (NODE.EQ.KCC(N,M)) THEN
             LIFT=M
          END IF
 40 CONTINUE
 50 CONTINUE
```

NODE is the boundary node which the routine is being called for (the cooling coil that the routine is being called for). The nodes position in the KCC array determines which lift it corresponds to and this number is LIFT.

```
C
    IF (TINC.LE.0.25 .AND. LIFT.EQ.1) THEN
       Y=Y25L600
    ELSE IF (TINC.GT.0.25 .AND. TINC.LE.0.5 .AND. LIFT.EQ.1) THEN
       Y=Y50L600
    ELSE IF (TINC.GT.0.5 .AND. TINC.LE.1.0 .AND. LIFT.EQ.1) THEN
      Y=Y1L600
    ELSE IF (TINC.GT.1.0 .AND. TINC.LE.5.0 .AND. LIFT.EQ.1) THEN
       Y=Y5L600
    ELSE IF (TINC.GT.5.0 .AND. TINC.LE.7.0 .AND. LIFT.EQ.1) THEN
       Y=Y7L600
    ELSE IF (TINC.GT.7.0 .AND. TINC.LE.14.0 .AND. LIFT.EQ.1) THEN
       Y=Y14L600
    ELSE IF(TINC.EQ.15.0 .AND. LIFT.EQ.1) THEN
       Y=Y15L600
    ELSE IF(TINC.LE.0.25 .AND. LIFT.EQ.2) THEN
       Y=Y25L480
    ELSE IF (TINC.GT.0.25 .AND. TINC.LE.0.5 .AND. LIFT.EQ.2) THEN
       Y=Y50L480
    ELSE IF (TINC.GT.0.5 .AND. TINC.LE.1.0 .AND. LIFT.EQ.2) THEN
      Y=Y1L480
    ELSE IF (TINC.GT.1.0 .AND. TINC.LE.5.0 .AND. LIFT.EQ.2) THEN
       Y=Y5L480
```

```
      ELSE IF (TINC.GT.5.0 .AND. TINC.LE.7.0 .AND. LIFT.EQ.2) THEN
         Y=Y7L480
      ELSE IF (TINC.GT.7.0 .AND. TINC.LE.14.0 .AND. LIFT.EQ.2) THEN
         Y=Y14L480
      ELSE IF (TINC.EQ.15.0 .AND. LIFT.EQ.2) THEN
         Y=Y15L480
      ELSE
         Y=Y15
      END IF
C
```

This loop determines what Y-values should be used based on the current increment time and the lift number. The reason this lift number is important is because different lifts have different lengths of coil which affects the Y-value. The last else statement is used as a default in case a time increment is used during the analysis that does not have a Y-value. This should *never* happen unless the user makes a mistake in implementing the procedure.

```
C
      CONCT=(KAVG(1,LIFT)+KAVG(2,LIFT))/2
```

The average concrete temperature for the boundary node considered is CONCT.

```
C
      IF (KINC.EQ.1 .AND. KSTEP.EQ.1) THEN
         U(1)=((YFI*(PT-WTEMP)+WTEMP)+WTEMP)/2
      ELSE
         U(1)=((Y*(CONCT-WTEMP)+WTEMP)+WTEMP)/2
      END IF
```

U(1) is the boundary temperature applied to the boundary node. If the analysis is at the beginning (increment and step 1), then the boundary temperature is calculated using the placement temperature of the concrete. If it is later in the analysis, the current concrete temperature (CONCT) is used instead.

```
C
      RETURN
      END
```

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14. ABSTRACT

Over the past decade, the U.S. Army Corps of Engineers has developed and implemented the use of NISA (nonlinear, incremental structural analysis) procedures to predict the effect of thermal loads due to the heat of hydration of cement in massive concrete structures during construction. To date, the commercial program ABAQUS has been used to perform a majority of the NISA's due to its versatility. Recently, a need to develop a modeling procedure for NISA's that can account for cooling coils placed within massive concrete structures has arisen. Often the heat generation within these structures cannot be controlled by changing the concrete constituents, reducing lift heights/widths, or modifying the construction procedures. Cooling coils placed within the concrete are needed to act as a radiator, constantly carrying heat from the source, the central region of the concrete, in order to reduce the thermal gradient within the material. A realistic method of modeling the effects of cooling coils in massive concrete structures is presented for both two-dimensional and three-dimensional analyses. The ability to capture the thermal changes in the concrete and cooling coils as they occur over time is the primary objective of the modeling technique. Previous to the modeling technique presented here, there was no acceptable procedure for modeling cooling coils and their effects within massive concrete structures using ABAQUS.

15. SUBJECT TERMS

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